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HANDS-FREE, PRECISION CONTROL FOR SMALL
HOVERING VEHICLES — A FLYING QUALITIES STUDY

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PREFACE

The work described in this document, except for the development of the research facility, was a portion of a study performed by the Research Department of Grumman Aircraft Engineering Corporation under NASA Contract NAS 2-2595, entitled "Research into the Use of the Human Balancing Reflex for Stabilization and Control of Vehicles in One-g and Sub-g Environments." The NASA technical monitor was Mr. Melvin Sadoff of the Ames Research Center, Moffett Field, California.

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ABSTRACT

An experimental study into the use of the human balancing reflex for control of small hovering devices was conducted. The principal tool was a simple two-degree-of-freedom simulator which permits a "flyer" to control horizontal translations with small tilting motions of a control platform on which he stands. A compelling advantage of balance reflex control is that the flyer's hands and conscious mind are freed from control functions and may be applied to other duties.

The present study, in which four flyers performed five different representative tasks with over 200 control system variations, determined what constitutes a good balance reflex control system, and how well balance reflex flyers can perform other duties. In general, it was found that balance reflex flyers can use their free hands to perform complicated tasks as skillfully as if standing on the ground. The best balance reflex control system has a gain of approximately 0.06 g's/deg, and a control platform with the smallest possible moment of inertia and some spring restraint.

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INTRODUCTION

The use of the human balancing reflex for vehicular control was first propounded publicly by Charles Zimmerman of the NACA in the early 1950's. His central thesis was that the learned pattern of reflexes used by a person in standing is essentially the same as that required to balance a force-vector supported platform, and hence should be directly applicable to the control of hovering-type vehicles. This concept and its simple but dramatic demonstration by Zimmerman (Ref. 1) piqued the imagination of many aeronautical engineers and led shortly to several experiments with free-flying platforms of various sorts. There were, for example, the ducted-fan machine of Hiller (Ref. 2), the stand-on helicopter of DeLackner (the "Aerocycle" tested by Princeton University Ref. 3), and several research-oriented devices built by the NACA (Refs. 4 and 5).

In much of this work, there seemed to be a tacit acceptance of the general concept, but only in its narrowest, most obvious application. Thus, the experimentation that followed effectively ignored the central theme in order to concentrate on aerodynamic and mechanical design problems of small, one man, transportation systems. In fact, it soon began to appear that the essence and significance of the original clean, elegant idea was being lost. The unfortunate result was an apparent consignment of a potentially valuable concept to oblivion, and a singular neglect of comprehensive research aimed at answering basic questions about how to exploit the human balancing reflex as a mechanism for vehicular control.

In the early 1960's, Grumman Research instituted an experimental program aimed at obtaining some fundamental answers regarding human balancing performance and its application to the control of several special classes of vehicles. The early work in this program, though exploratory in nature, was one of the first attempts to assess the effects of platform and system dynamics on performance of the human balancing reflex as a control mechanism. It clearly demonstrated a strong influence of platform characteristics on system stability, and showed that the simple configuration used by Zimmerman was not optimum (Ref. 6). These results gave impetus to the present, more comprehensive study of how platform and system dynamics affect flying qualities and a flyer's ability to perform useful duties.

BASIC PRINCIPLES

There is some question about the significance of the word "reflex" in the context used here. The question is not trivial, as it might at first seem, because the more elemental a pattern of neuromuscular responses, the more it can be relied upon to perform properly under conditions adverse to the higher neural processes. At least some physiologists (for example, Ref. 7) hold that the human balancing ability, though requiring a complex and delicate neuromuscular behavior, stems from a learned coordination of many simple reflex arcs similar to the one involved in the common knee-jerk reflex. There seems reason to believe, then, that ordinary balancing involves only elemental neural processes, and is in effect a "learned" reflex.

A person standing on the floor remains balanced by making ceaseless but completely unconscious fine adjustments of his foot and leg muscles in response to several classes of stimuli, primarily (in normal people) those from the acceleration sensing organs of the inner ear. If a person is forcibly tilted forward or backward he instinctively pushes with his toes or heels to remain balanced. If he stands on a rug which is pulled gently forward, he is tilted gently backward and instinctively responds with an appropriate heel pressure, expecting (subconsciously) to right himself thereby. It is thus clear that when a person pushes with his toes or heels, he expects (subconsciously) to be tilted backward or forward. Suppose now that a person standing on a rug can control with his feet the force with which the rug is pulled: when he pushes his toes down the rug accelerates forward, when he pulls his toes up the rug accelerates backward. This, of course, can be interpreted as, "toes down, tilt backward; toes up, tilt forward," which is precisely the response he needs to keep himself balanced.

Zimmerman reasoned that a jet thrust device attached to the feet would provide appropriate tilting moments in response to foot motions, and thus be readily controlled.

THE EXPERIMENT

An Overview

Zimmerman and others have clearly demonstrated the basic soundness of the balancing-reflex-for-control idea; there is no question that a flyer can, with little or no practice and without conscious effort, stand on, stabilize, and maneuver a small hovering vehicle by using his feet alone. Thus the crucial question that this experiment was designed to answer became: How well can a flyer perform additional useful duties while controlling one-g hovering vehicles using his natural balancing-reflex and what constitutes a good balance reflex control system?

Toward this end, five distinct tasks to be performed by a flyer while operating a simulated balance reflex controlled vehicle were devised. Each of these tasks was an abstraction of a type of job that might logically be performed in the real world and was designed to demand a reasonable amount of concentration by the flyer. In addition, four control system parameters which affect the dynamic response of the system and which have basic engineering significance were chosen as variables. Three of these, platform spring rate, platform damping, and platform moment of inertia relate to the "feel" of the control element while the fourth, system gain, relates to the dynamic response of the entire man-vehicle system.

In the most general terms, the experiment consisted of four subjects flying various configurations* of the simulator, performing a number of "tasks" during each flight, obtaining a score for each task, and rating each configuration's suitability for each task.

The experiment was performed in two separate parts: a longitudinal part in which the flyer faced in the direction of motion of the simulator, and a lateral part in which the flyer faced crosswise to the direction of motion of the simulator. Data gathering absorbed about 30 working days, during which each flyer "logged" about 30 hours of flight time.

* A "configuration" is a particular combination of specific values of the four independent parameters of the study.

The Simulator

The simulator (Fig. 1) is a hydraulically driven carriage which permits a pilot to make limited (8 feet) horizontal excursions in response to tilting motions of a control platform on which he stands. The device is intended for use primarily as a tool for the study of balancing, but a limited feel for maneuvering characteristics can be obtained within the 8-foot confines. The carriage is propelled by a hydraulic motor driving a horizontal screw jack. A small analog computer accepts platform tilt signals and provides appropriate motor control signals to make carriage acceleration proportional to platform tilt angle.

The basic unit incorporates a mechanical system, consisting of interchangeable torsion-bar springs, eddy current dampers, and flywheels, to provide the platform rotational dynamic factors: moment of inertia, rate damping, and spring constant. Figures 2 and 3 show the arrangement. This system was adopted only after a protracted effort failed to improve significantly an erratically behaving hydraulic servo drive which had been used for simulating platform rotational dynamics during most of the previous work on the simulator. It had long been realized that small amounts of deadzone and stiction in the servo control valve were producing anomalies in the system behavior. During the early, exploratory phases of the work, these anomalies could be lived with, but as the need for more accurate simulation grew, the hydraulic system had to be abandoned in favor of the less flexible but more realistic mechanical system.

One side effect of the change was that the maximum damping dropped to about 10 percent of that previously obtainable. Successful fluid dampers might have been developed to cover the larger range, but there was not sufficient time to pursue this tack. The enforced reduction in damping range, though unfortunate in some respects, nevertheless permitted the simulation of a fairly large class of small, one man, hovering type vehicles for which the balance reflex control concept would be extremely useful and in which damping is by nature small.

A secondary result of the change to a mechanical system was that changing platform parameters, which had been a simple matter of turning several thumbwheel switches on a control panel, became a fairly arduous and time consuming operation.

Tasks

It appears that the balance reflex control concept can most readily be applied to small, one man, hovering vehicles. What sort of jobs, then, might the flyer of such a vehicle be asked to perform? They would be small, one man operations such as surveillance, weapon aiming and firing, inspection, assembly, or minor repair of equipment in inaccessible places, conveyance of relatively light parcels over short distances, and possibly some form of tracking of a moving target. Accordingly, the following five tasks were devised to represent some of these jobs:

A. Off-board dexterity task

In general, this task was designed to measure the flyer's ability to perform complex, delicate, manual tasks external to his vehicle. It was an abstract representation of the light assembly and repair function. Specifically the flyer held himself close to a fixed table and performed a variant of the standard Crawford Small Parts Dexterity Test (see Fig. 4): using a pair of tweezers, he transferred small pins from one set of holes in a flat plate to another, then covered them with small collars taken from a second group of pins.

B. On-board dexterity task

This task was the same as above, but performed at a table attached to the vehicle (see Fig. 5). It was designed to measure the flyer's ability to perform complex delicate assembly, repair, or adjustment functions within the vehicle.

C. Gross dexterity task

In general, this was a measure of the operator's ability to apply forces and to handle unwieldy objects with precision. It was an abstract representation of a "heavy" construction function or a loading and unloading function. Specifically, the flyer was required to remove, one at a time, four, fairly heavy (18 lbs) steel plates from a pair of close fitting pegs and place them on a second (lower) set of pegs (see Fig. 6).

D. Aiming task

This was a fairly specific representation of an important combat or surveillance function. Specifically, the flyer was required to aim a rifle-like device at a remote, fixed target (see Fig. 7).

E. Tracking task

This was a fairly abstract representation of the class of functions in which the vehicle must follow a moving reference or aim at a moving target. Specifically, the flyer was required to align an indicator fixed to the vehicle with a randomly moving target (see Fig. 8). The target moved proportionally to a pre-recorded, repeatable, 100 second sample of filtered, gaussian, white noise. The resulting motions had a band width of 0.0016 to 0.12 cps, and a standard deviation of 6 in.

It is worthwhile noting that the peculiarities of each task imposed different secondary requirements on the flyer. For instance, the aiming task limited the flyer's visual reference cues, the gross dexterity task forced him to contend with an abrupt and significant center of gravity shift, and the off-board dexterity task required him to maintain a fairly stationary position with his upper body.

Measurements

Two types of measurement were recorded: task performance, called the "score," and the flyer's quantified opinion of vehicle desirability, called the "rating." The scores for the three dexterity tasks were the times required to do them. The scores for the tracking and aiming tasks were the absolute values of the tracking and aiming errors integrated over 40 and 100 seconds, respectively.

Flyer opinions were quantified using a four point rating scale ranging from "bad" (1) to "excellent" (4). In the event a flyer could not control a given configuration, i.e., lost control and had to abort the flight, a rating of "zero" was recorded.

This scale was not as finely graded as the 10 point Cooper scale used by qualified pilots for aircraft handling studies, but it was believed to be the only thing practical in view of the over-all lack of experience with balance reflex control systems.

It should be emphasized that the flyers rated a configuration after performing each task. Thus, the same configuration conceivably could be rated "1" for one task and "4" for another.

All subjects practiced performing all tasks while flying a variety of configurations before formal testing began. After sufficient practice to achieve a learning plateau, all subjects established "static" norms in the experimental setting with the carriage and platform locked. These norms were specified as the average score for 10 consecutive runs. A norm could not be established for tracking, however, because carriage motion is an intrinsic part of the task.

Concomitant with the present flying qualities study was a basic study of the mechanics of human balancing. Some of the data for that work were recorded on magnetic tape during the present experiment in the form of motion time histories of various system components (e.g., carriage and platform).

Subjects

Four subjects participated in the experimentation. One had worked with the simulator since its inception and had by far the most familiarity with and practice on the machine. Two others, with less total flying time to their credit, nevertheless were very familiar with the equipment and had considerable experience. The fourth began as a naive subject but was given every opportunity to practice with a large variety of configurations before the actual testing began. Thus, it is believed that all of the flyers could be classified as experienced.

Conduct of the experiment required the attention of two people at all times. For economy of personnel, therefore, the flyers doubled as experimenters when they were not flying. A pilot study was performed to check out equipment and procedures, and during this phase each flyer was trained to do the experimenters' various chores.

Parameters

In all, four parameters were investigated. Three of them affect the "feel" of the control platform. These are 1) platform spring rate, 2) platform damping, and 3) platform moment of inertia. The maximum values of spring constant and moment of inertia, 28 ft-lbs/deg and 163 slug-ft², respectively, were chosen by a subjective consensus of what felt "very stiff" and "very heavy." The maximum damping of 0.44 ft-lbs/deg/sec was the largest obtainable. Three other values of each of these parameters were selected at equally spaced increments on a subjective (rather than a physical) scale. The subjective scaling process is discussed in Ref. 6.

The fourth parameter investigated was system gain (g's of carriage acceleration per degree of control platform tilt). The maximum practical gain is that at which the system becomes unstable, and is a function of the three platform parameters. To ensure that all configurations would be stable, the data of Ref. 6 were used to indicate the value of gain that is less than, but close to, the maximum for each set of platform parameters. Thus, the values of gain investigated were not the same for every combination of spring, damping, and inertia, and a total of seven (used four at a time) were required.

Run Schedule

The most effective run schedule would have been one that was completely randomized with respect to the order in which the configurations were flown, the tasks were performed, and the subjects flew. In this experiment, however, it was simply too arduous to change the configuration after every flight and so all four subjects flew each configuration before it was changed. The order in which the subjects flew was randomly changed twice a day, as was the order in which tasks were performed during each flight.

At least one overt effect of order is known. The gross dexterity task required an appreciable amount of muscular activity and the flyers tended to be somewhat "jittery" after performing it. Even though it became standard procedure to relax for 10 or 20 seconds after this task, a certain amount of degradation in the performance of succeeding tasks might be expected. It is believed, however, that the twice-daily random change in task order was sufficient to "eliminate" any bias caused by this effect.

Lateral vs. Longitudinal Study Effort

As stated, the experiment consisted of two parts: 1) a longitudinal part in which the flyer controlled fore and aft motion by tilting the platform with ankle deflection; and 2) a lateral part in which the flyer was turned 90 degrees and controlled sideward motions by tilting the platform with differential foot lifting.

The longitudinal experiment consumed approximately 80 percent of the test effort. Here, all four subjects performed each of the five tasks, for each of 256 test configurations (4 levels each of spring, damping, inertia and gain).

The lateral experiment was performed after all longitudinal data had been collected and analyzed. Limited resources forced truncation of the lateral experiment, and the results of the longitudinal study were used to indicate the most efficient way to do this. In all, two flyers performed three tasks (off-board dexterity, aiming, and tracking) with 72 configurations which combined the 2 extreme values of damping with 3 levels of spring, 3 levels of inertia, and 4 levels of gain.

Data Analysis Procedure

Score and rating data had been collected and punched into paper tape automatically, so that initial preparation for analysis consisted primarily of processing by high-speed digital computer and automatic plotting. In the longitudinal case, the data were fitted by least squares to five dimensional, complete cubic polynomials. Such polynomials have 35 constants to be determined, so that the 256 data collected for each flyer and task provided more than 7 points per coefficient. (For a more comprehensive discussion of the philosophy of such polynomial data fitting, see Ref. 6.)

Polynomials were not computed for the lateral case because of the sparsity of data. Instead, the data were averaged and plotted directly on the longitudinal graphs for direct comparison of the two cases.

Most of the graphic representations of the results, which are discussed at length in the Results Section, are cross sectional plots of the five dimensional hyper-surfaces fit to the longitudinal data.

RESULTS AND DISCUSSION

For an initial look at the data was desired to appraise flyer variability and the gross effects of the experimental variables. To this end, score and rating were plotted against gain for each task and flyer at all combinations of platform spring, damping, and moment of inertia. A typical example of these first plots is shown in Fig. 9.

Several facts stood out quite clearly: 1) The flyers were in substantial agreement about flying qualities (rating data) and they performed similarly (score data); 2) the effect of damping is virtually nil; 3) the results of the gross and off-board dexterity tasks were very similar; and 4) the results of the on-board dexterity task were the least sensitive to parameter variation.*

Under the conclusion that the flyers are similar and damping is negligible, the initial plots could be simplified by averaging the results across all pilots and damping values. Thus, the curves in Figs. 10 through 13 are cross sections of polynomial hypersurfaces fit to these average longitudinal scores and ratings. The square symbols appearing on each plot represent the average longitudinal scores or ratings to which the surfaces were fit, and the vertical lines through them depict the standard deviation in score or rating. Small x's just above the abscissas mark configurations** that are unstable, and for which no scores or ratings were obtained.

* These facts suggested that the lateral experiment could reasonably be truncated to two subjects, three tasks, and two levels of damping. In fact, even this degree of truncation did not appear to be enough for the resources remaining, and a further, arbitrary truncation to three levels of spring and inertia, and four levels of gain was made.

** Despite efforts to study only stable configurations by selecting them from the stable region defined in Ref. 6 (see Parameters, p. 8), several of the higher gain configurations were found to be unflyable. It is believed that the artifacts of the simulator used in Ref. 6 (see The Simulator, p. 4) and the competitive nature of that experiment, in which subjects tried to fly the highest gains possible, combined to produce a stable region containing some gains that were too high.

The round symbols shown on some of the curves represent the average scores or flyer ratings obtained from the lateral study. These data were superimposed on the longitudinal results (polynomials were not fitted) to allow some simple but direct comparisons of the two cases.

We will examine Figs. 10 through 13 with the two basic objectives of the study in mind, that is, to determine: 1) from the flyer's point of view, what constitutes a good balance reflex control system, and 2) how well can a balance reflex flyer perform useful duties with his free hands? It turns out, as is shown by the data presented in Figs. 10 through 13, that the relatively few lateral data points are not at variance with corresponding longitudinal data points. Therefore, the arguments that follow are based upon examination of the more complete longitudinal results, under the assumption that all major conclusions apply equally to the lateral case.

The rating data presented in Figs. 10, 11, and 12 are the most appropriate for discussing what the flyers think are the best combinations of spring, gain, and inertia. Figure 10 clearly demonstrates that spring is highly desirable for all tasks and at all levels of gain and inertia, and that the particular shapes of the rating versus spring curves are essentially alike from task to task, with but one exception: for the tracking task (Fig. 10e), the flyers do not consider more spring always desirable; at the lower levels of gain and inertia there is an optimum spring rate of approximately 15 ft-lbs/deg.

Another significant feature, which pervades all the tasks, is the nonlinear effect of spring: going from zero to approximately 12 ft-lbs/deg of spring in most cases produces almost all the benefit that can be derived.

In general, then, flyers consider platform spring to be highly desirable, and about 12 to 15 ft-lbs/deg seems to be a good, practical design range for all tasks over a wide variety of inertia and gain values.

Increases in moment of inertia turn out to be never beneficial, and, in most cases, highly undesirable. The flyers' strong dislike of anything but the lowest inertias (under 5 slug-ft²) is amply

displayed in Fig. 11. They are most critical of higher inertias when performing the tracking task, and least critical when performing the on-board dexterity task, but even there, inertia is not beneficial. It is appropriate to note that the tracking task is the only one in which purposeful maneuvering of the carriage is required; in the off-board dexterity, gross dexterity, and aiming tasks, only stabilization with reference to a fixed object is necessary, and in the on-board dexterity task even that requirement is essentially missing. It seems completely reasonable that an undesirable characteristic such as high inertia should be more strenuously denounced in tracking tasks than in stabilization tasks, especially undemanding ones. The dislike for inertia is mitigated somewhat in low gain, high spring-rate configurations, except for tracking, where these configurations are not very desirable, even with the lowest inertia.

In general, then, for a device to be pleasant to stabilize and control, inertias must be small.

Under the conclusions that a balance reflex control system should have very low inertia and moderate spring (approximately 12 to 15 ft-lb/deg), the data of Fig. 12 reveal the best gain. For the lowest inertia (0.8 slug-ft^2) and a spring rate close to the optimum (11 ft-lb/deg), there is a gain of 0.06 g's/deg which the flyers consider the most desirable for all tasks.

This completes the answer to one of the basic questions: What constitutes a good balance reflex control system? Clearly, damping is unimportant (over the range tested),* moment of inertia should be as small as possible, and spring rate should be 12 to 15 ft-lb/deg, and gain should be about 0.06 g's/deg .

Some interesting comparisons can be made with the results of the previous study (Ref. 6), in which the limit gain for arbitrary "move and stop" maneuvers was the objective. The flyer's impressions of the effect of gain were summarized there as follows:

*The negligible effect of damping is somewhat surprising, but it is conjectured that larger values than could be achieved here ($0.44 \text{ ft-lb/deg/sec}$) might, in fact, begin to show some effect.

"... increasing the system gain turned out to be generally beneficial, up to a point. Beyond this, the dynamic stability of the man-machine system deteriorated rapidly, a violent uncontrolled oscillation marking the absolute limit."

This implies that the best gain is very close to the limit gain. The results of the present study, which were obtained with more precision, show that this inference is in error. Data from the tracking task (Fig. 12e), which is most similar to the arbitrary "move and stop" maneuvers of the previous study, show that increasing the gain is indeed beneficial at the lower levels (except perhaps for the highest value of inertia considered), but that the "best" value occurs well before the system becomes unstable.

The present data do, however, support the use of limit gain as a rough figure of merit, as in the previous study. Again, Fig. 12e indicates that limit gain (the measured or extrapolated gain at which the system becomes unflyable) generally gets smaller as inertia is increased, and larger as spring is increased. Thus, using limit gain as a figure of merit does lead to the proper conclusion, as in Ref. 6, that inertia is detrimental and spring is beneficial.

The score data presented in Fig. 13 are appropriate for discussing the flyers' ability to perform useful duties. Grey bands on the plots of off-board dexterity, on-board dexterity, gross dexterity, and aiming scores (Fig. 13, parts a, b, c, and d) depict the standard deviation of scores achieved by subjects' doing the tasks "on the ground" (see Measurements, p. 6). An obvious and very significant observation can be made immediately: With almost all the configurations that could be flown, the tasks were performed as well while flying as they were on the ground! This is most dramatically shown for each of these tasks, at an inertia of 28 slug-ft² and a spring of 19 ft-lb/deg. Here, through the first five levels of gain, the flyers perform without decrement even though the rating data (Fig. 12, parts a, b, c, and d) reveal the flyers' displeasure with the higher gain configurations. Finally, at the next level of gain, the system becomes unflyable and no score is recorded. Thus, balance reflex flyers can control even poor configurations well enough to do tasks requiring only vehicle stabilization as well while flying as they do on the ground. The flyers do state a belief, however, that performance would suffer if the poorer configurations had to be used in the presence of external disturbances or for protracted tasks.

The tracking error scores (Fig. 13e) are interestingly different. Actually, because there is no norm for these scores, it is hard to attach any meaning to the numerical values, but it is significant that the best scores are obtained with the same configurations that the flyers like the best (i.e., very low inertia, moderate spring, and moderate gain). Furthermore, the score versus gain curves are similar in shape to the rating versus gain curves for this task (Fig. 12e). This means that, for balance reflex tracking, performance is a keen discriminator of flyer preference. Also, because the stabilization task scores are relatively insensitive to platform characteristics, a balancing reflex controlled vehicle that is good for maneuvering tasks is also good for stabilization tasks. These are somewhat rare occurrences for control systems which use man as an active element. It would be hazardous to generalize these conclusions, however, because only one, arbitrarily chosen, forcing function bandwidth (0.0016 to 0.12 cps) was investigated, and it may not represent any real balance reflex tracking task.

Now, the second basic question — how well can a balance reflex flyer perform useful duties with his free hands? — is answered: Performance of relatively short term stabilization tasks can be performed as well by a balance reflex flyer, with almost any configuration that is flyable, as by a person standing on the ground. The anticipated effects of external disturbances and fatigue during longer term duties, however, suggest that only the best liked configurations (very low inertia, moderate spring, and moderate gain) are practical. Furthermore, the best liked configurations are also the best to track with.

The fact that the scores obtained while flying do not significantly differ from the static norms is not too surprising if it is viewed in the following way. It is a long established fact that man is a most adaptable control element. He adjusts his internal parameters over a wide range to complement physical system parameters so as to maintain the combined man-machine performance. This observation applies equally well to the balance reflex mode of control. A dramatic demonstration occurs when a flyer operates a zero-force platform. With high gain, he stands quite still (except for some small, random-looking foot motions) while performing the various tasks, and as the system gain is lowered, only his foot and leg motions increase. With the lowest flyable gains, his legs may thrash around dramatically, but his upper body remains fairly still. He may not like this configuration and he may get tired flying it,

but he can and does do the assigned task very well because his shoulders are stable. If there is a fair amount of spring in the platform, his performance can remain constant all the way down to zero gain because he can maintain his balance using spring torque alone. If both spring and inertia are present, the same argument holds, but with the reservation that at higher gains the vehicle can get out of control quite easily.

It is important to remember that the foregoing discussion applies equally to the lateral and longitudinal control modes. Thus, lateral and longitudinal balance reflex control systems should be identical. This simple fact (which should be verified in a situation where both modes are controlled simultaneously) allows one to envision balance reflex control vehicles which are symmetrical about the flyer's spine, and on (or in) which he can stand facing in any direction. Such a device would have obvious utilitarian advantages.

We have analyzed the results and found the configurations that the flyers like the best, and that allow the best performance of various tasks. Neither ratings nor scores, however, can convey the feeling of confidence that an experienced flyer has with an optimum configuration. It is difficult to describe this feeling, other than to say that flying an optimum configuration is "just plain fun." This is not a very sophisticated description, or a very adequate one, but none better is at hand. The fact is, that good configurations feel to the flyer like normal extensions of his body which provide proper accelerations in response to wholly natural, "unconscious" foot motions. Indeed, if the flyer makes a conscious effort to control, which is often the plight of the neophyte, he invariably does it wrong and loses control. It seems as if the balance reflex flyer just naturally knows what he wants to do, and somehow does it.

SUMMARY OF MAJOR CONCLUSIONS

1. Balance reflex flyers can use their free hands to perform complicated tasks as skillfully as if standing on the ground. This is true even when the control configuration is so far from optimum that the man-machine system borders on instability, at least for relatively short tasks performed without external disturbances.
2. The best balance reflex control system for small hovering devices has a gain in the vicinity of 0.06 g's/deg , the smallest possible platform moment of inertia, and moderate platform spring (vicinity of 12 ft-lb/deg).
3. Platform spring restraint is generally beneficial, platform moment of inertia is always detrimental, and platform damping (up to $0.44 \text{ ft-lb/deg/sec}$) has no significant effect.
4. For small hovering devices, lateral and longitudinal balance reflex control system requirements are identical.

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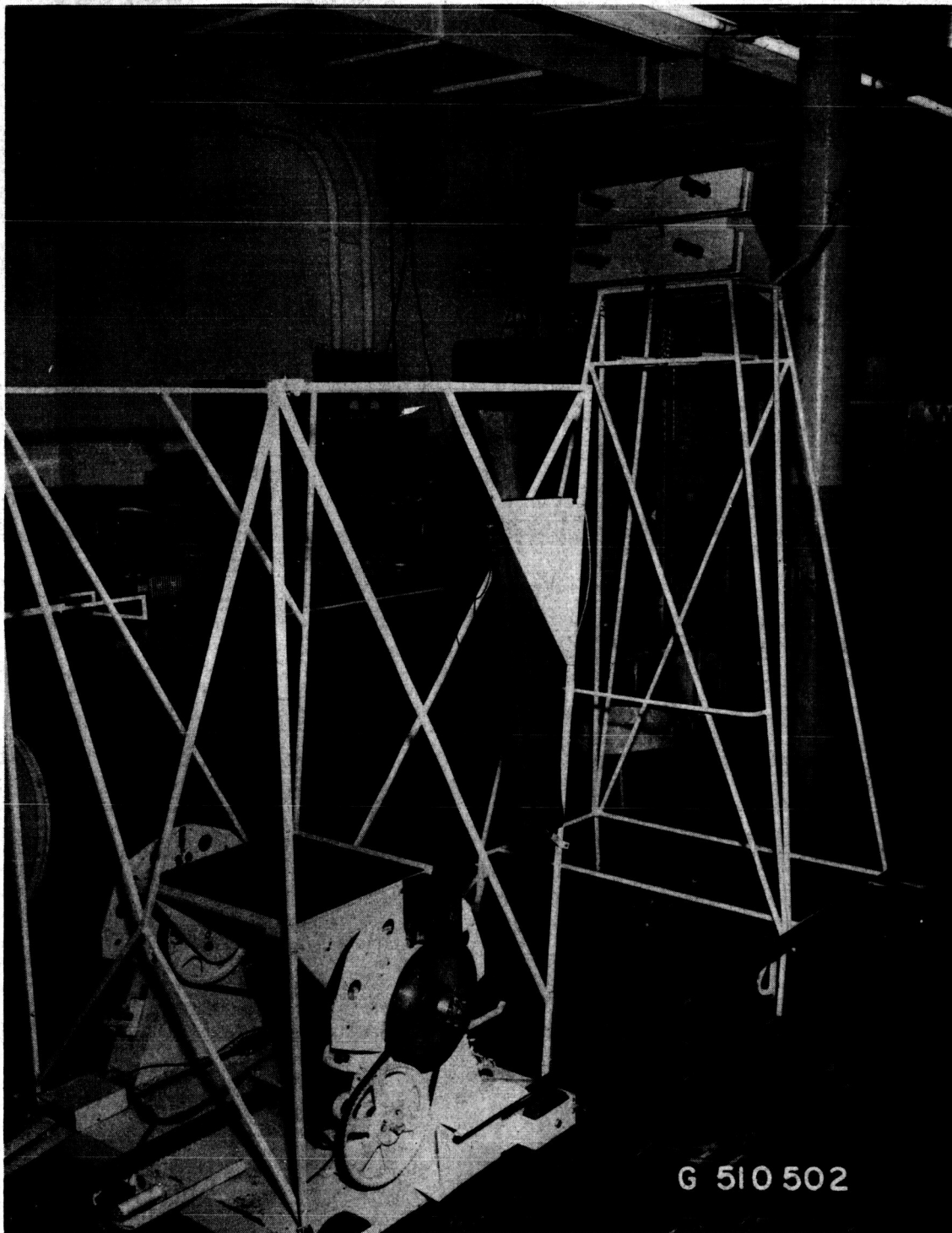


Fig. 1 The Simulator and Associated Equipment

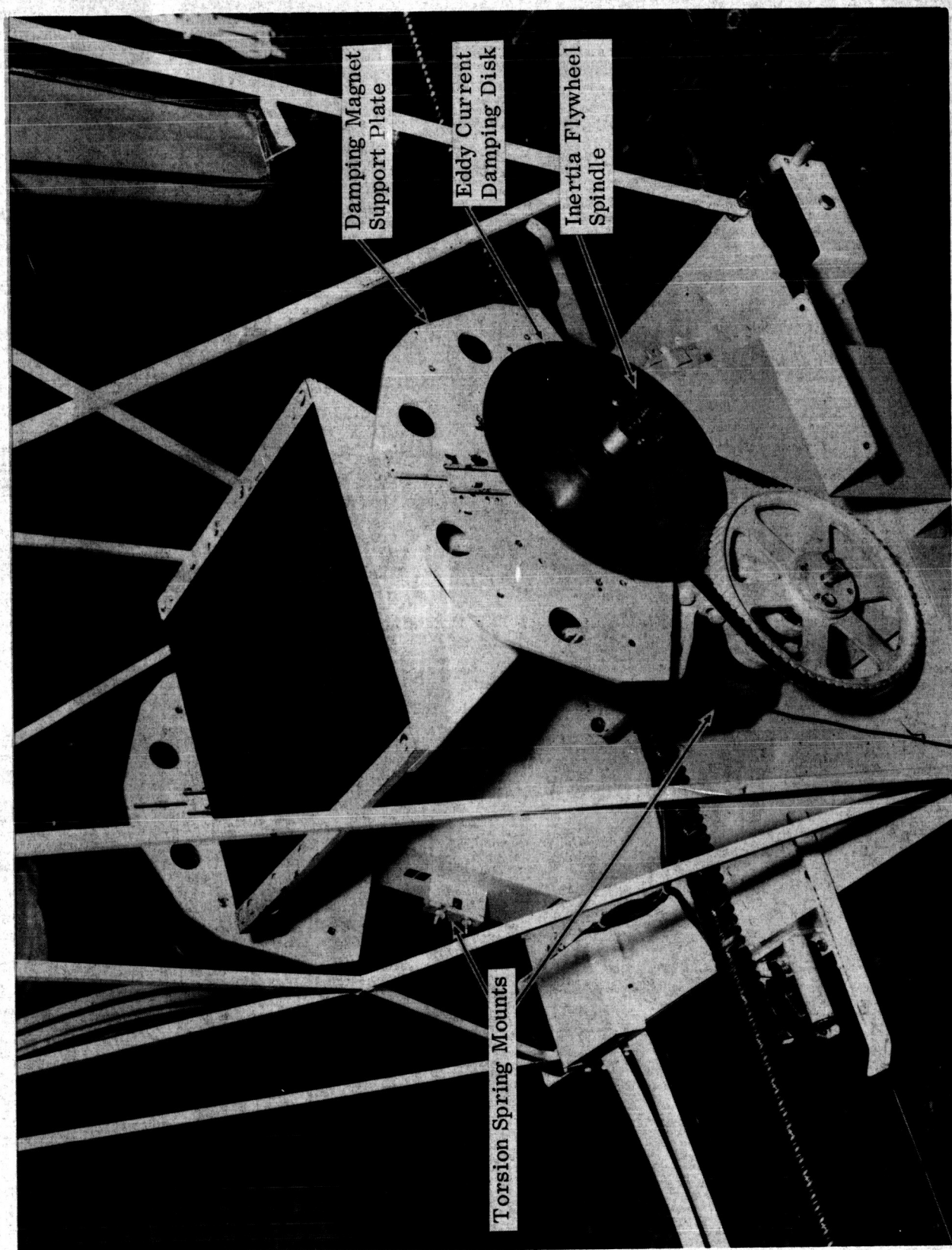


Fig. 2 The Simulator Carriage Showing Platform
Force Mechanisms (Zero Force Configuration)

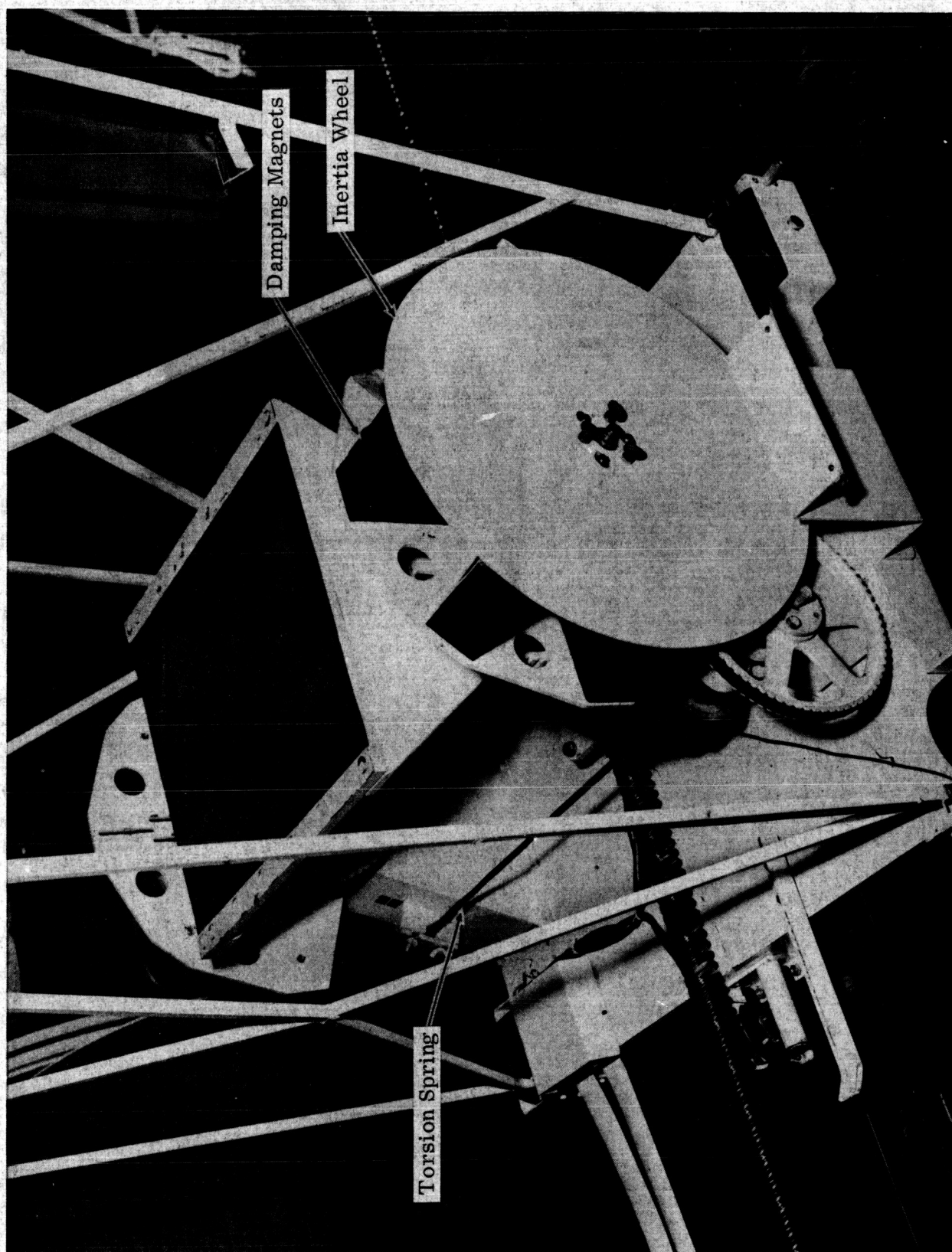


Fig. 3 The Simulator Carriage; Typical Inertia Wheel, Torsion Springs, and Damping Magnets in Place (Only One Side Shown)

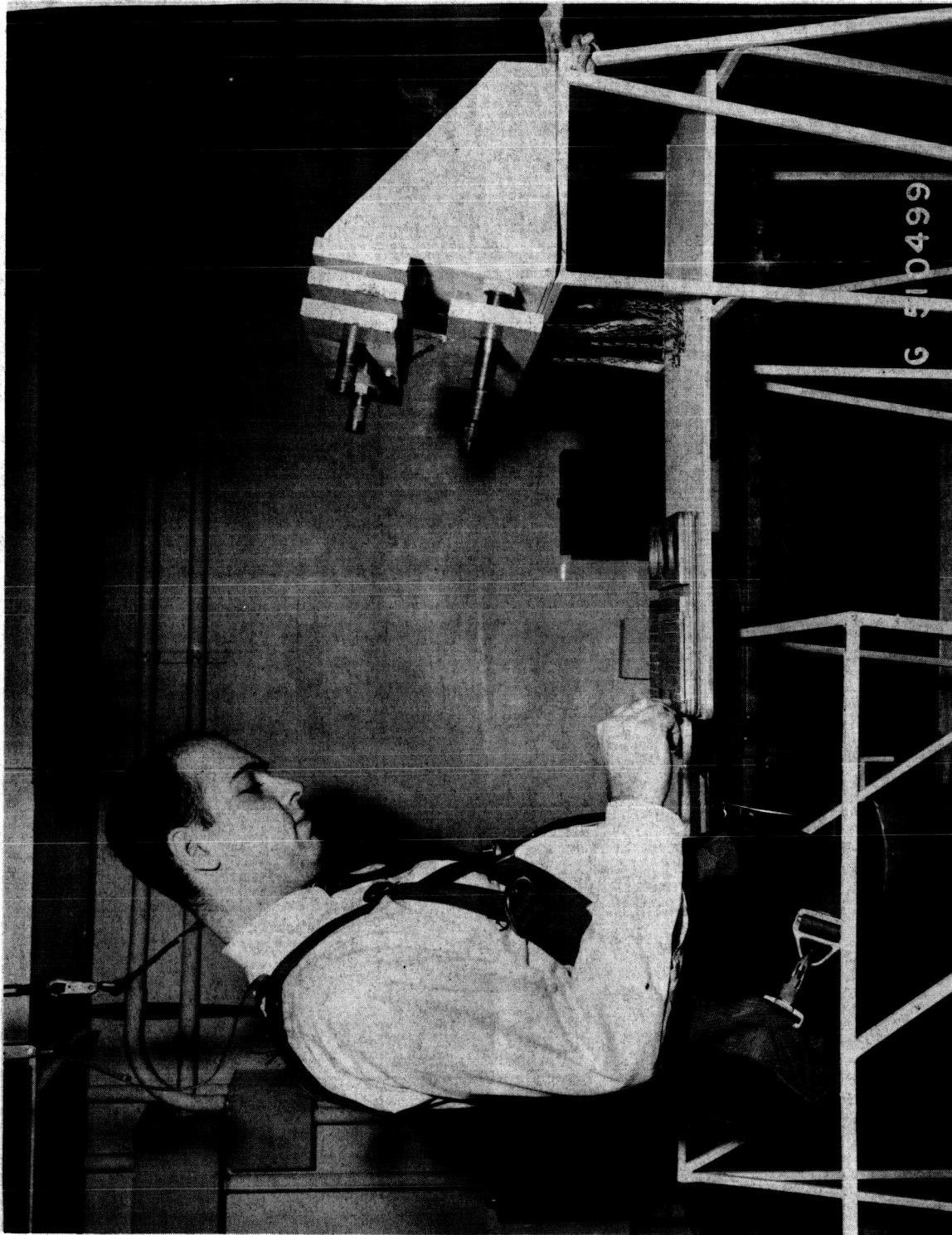


Fig. 4 The Off-Board Dexterity Task Being Performed

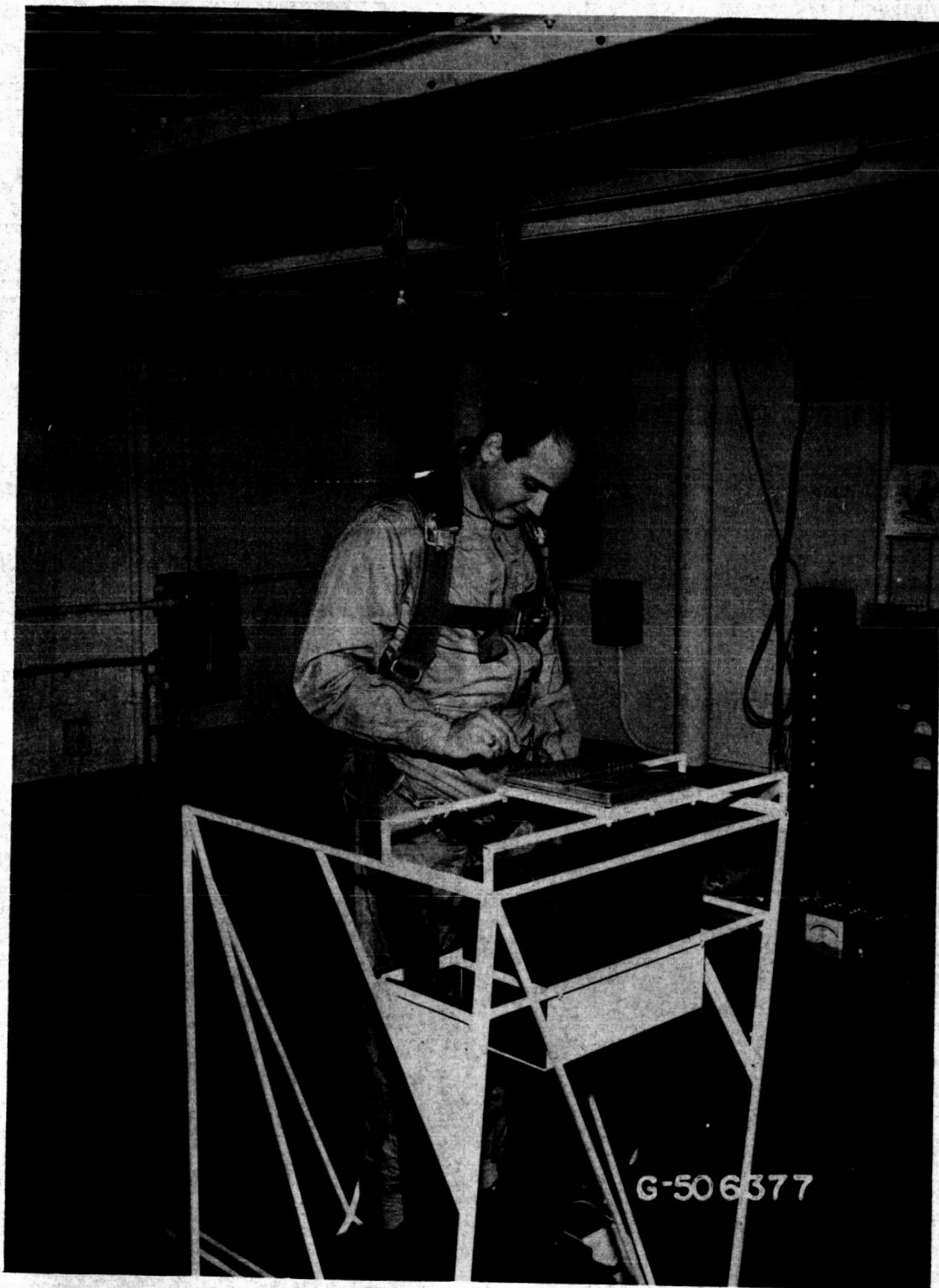


Fig. 5 The On-Board Dexterity Task Being Performed



Fig. 6 The Gross Dexterity Task Being Performed

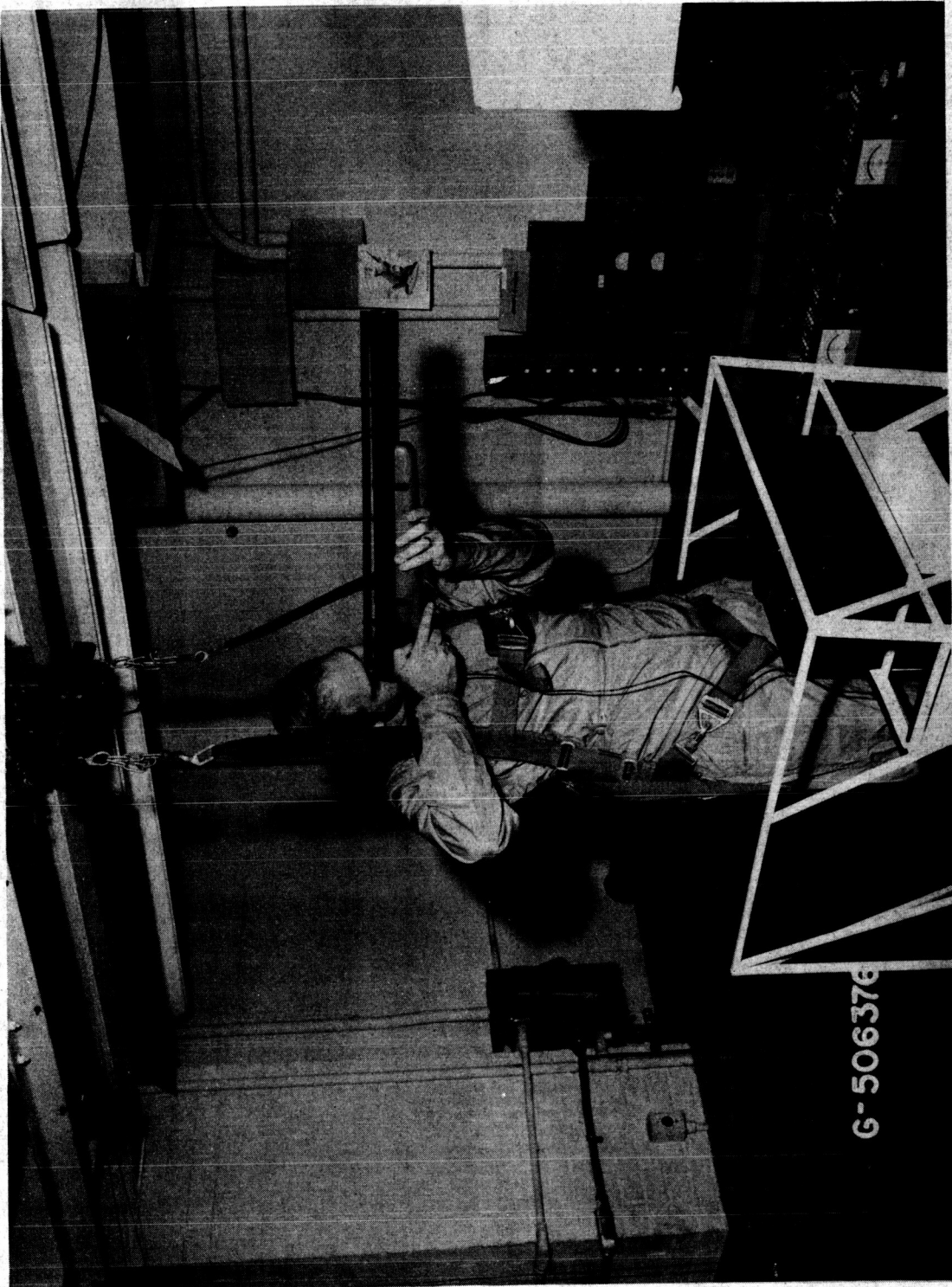


Fig. 7 The Aiming Task Being Performed

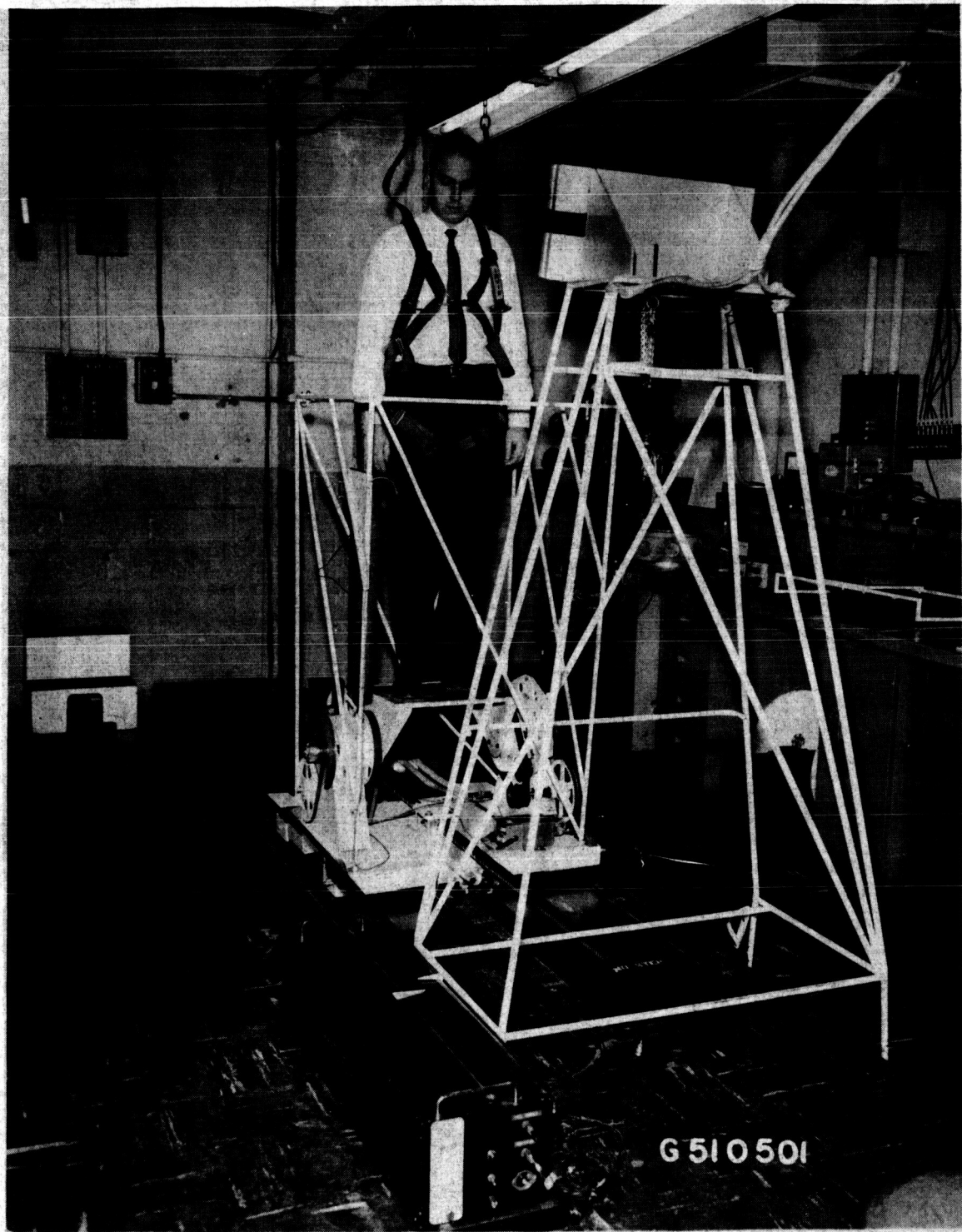


Fig. 8 The Tracking Task Being Performed

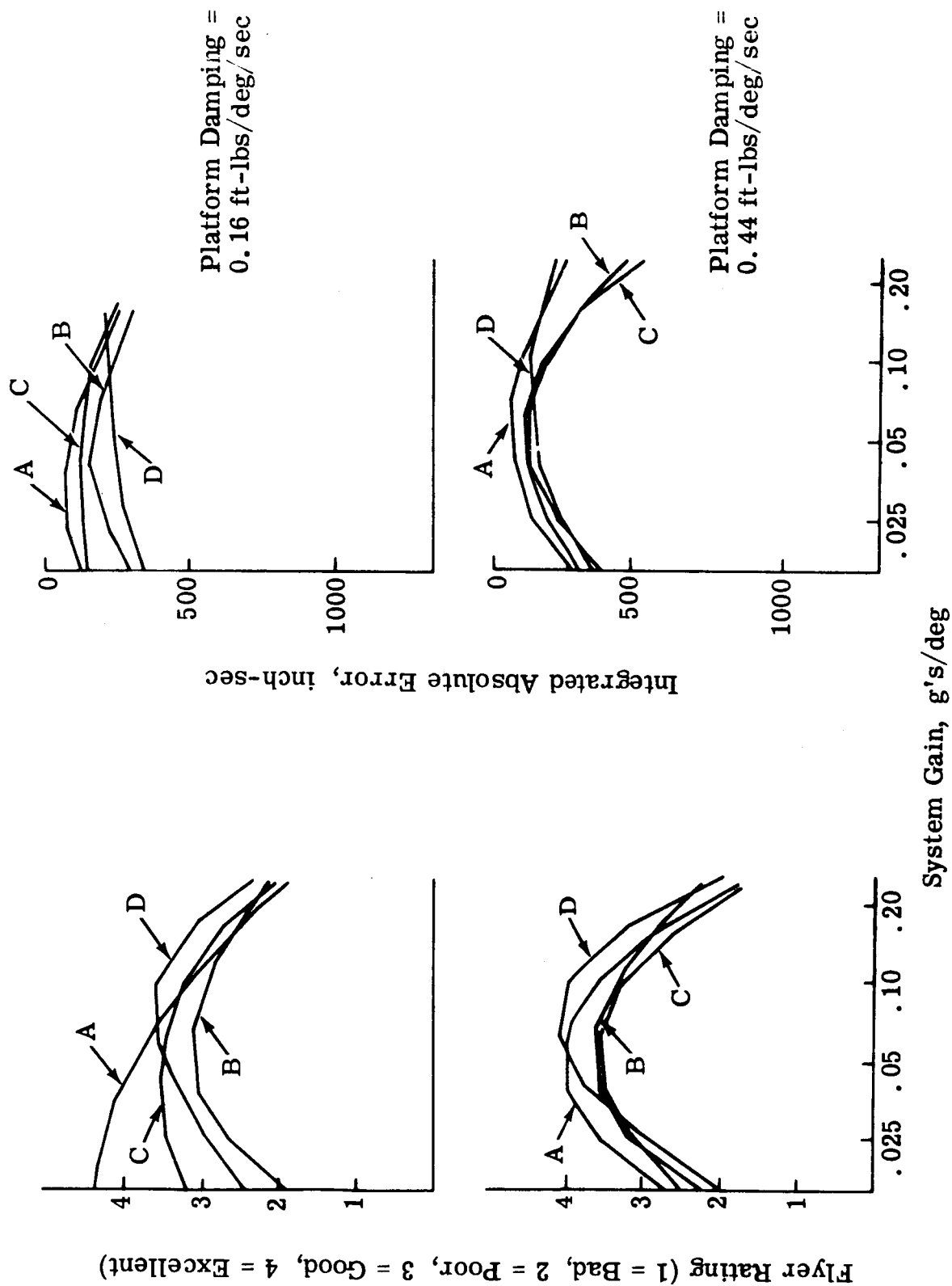


Fig. 9 Four Flyers' Typical Score and Rating as a Function of System Gain:
Tracking Task (Platform Spring = .11 ft-lbs/deg, and Platform Moment
of Inertia = 5 slug-ft²)

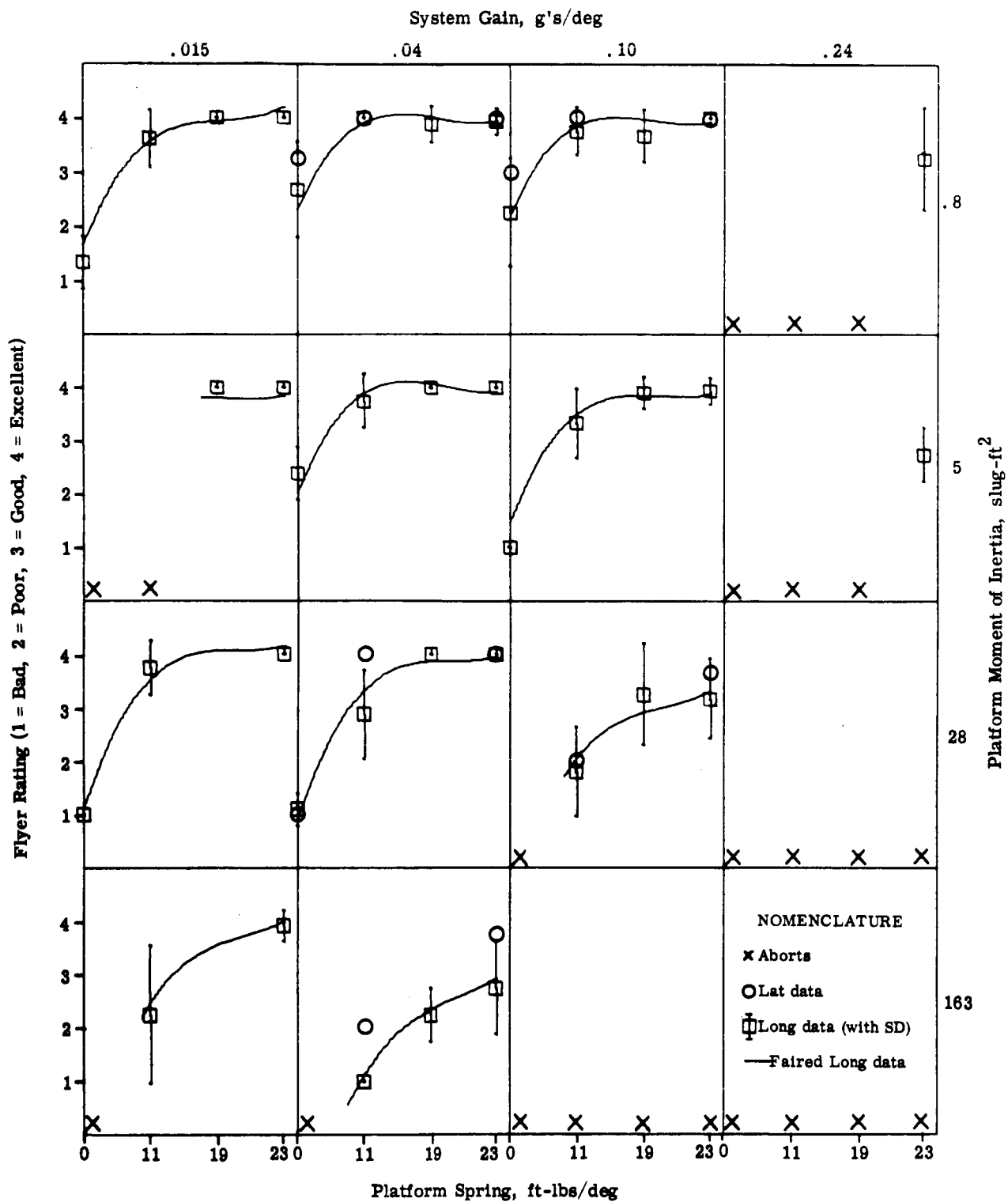


Fig. 10a Average Flyer Rating as a Function of Platform Spring (Off-Board Dexterity Task)

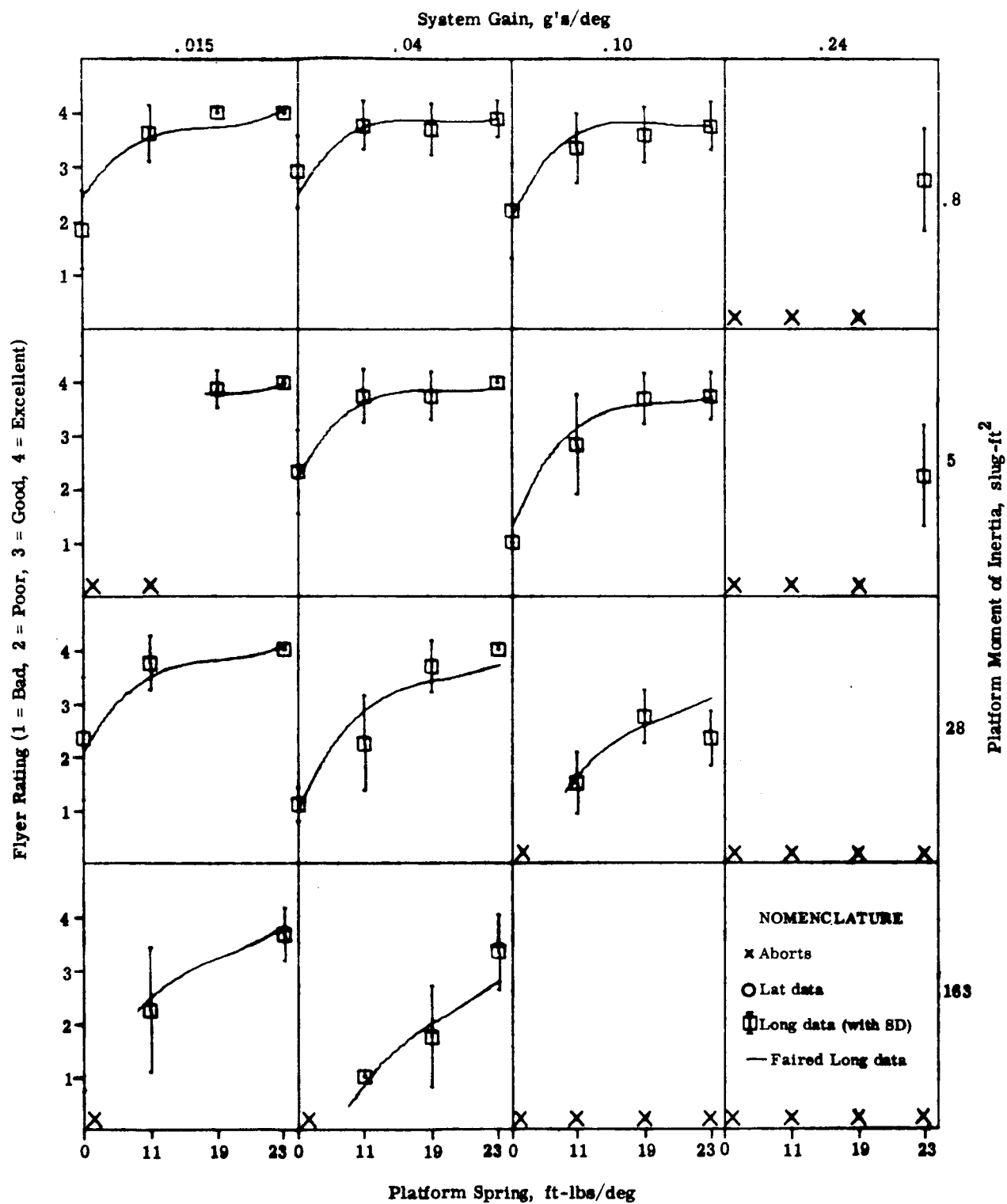


Fig. 10b Average Flyer Rating as a Function of Platform Spring (Gross Dexterity Task)

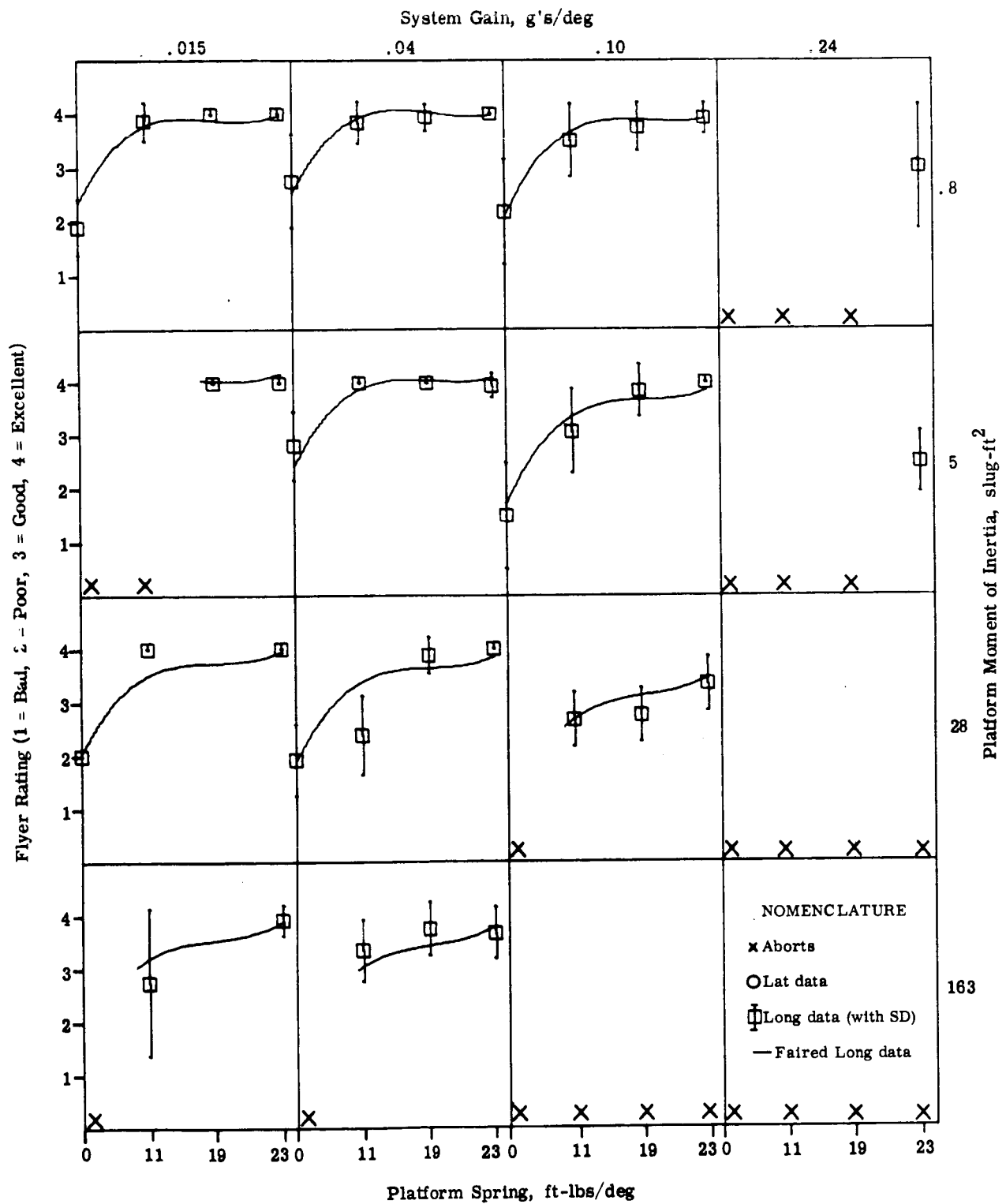


Fig. 10c Average Flyer Rating as a Function of Platform Spring (On-Board Dexterity Task)

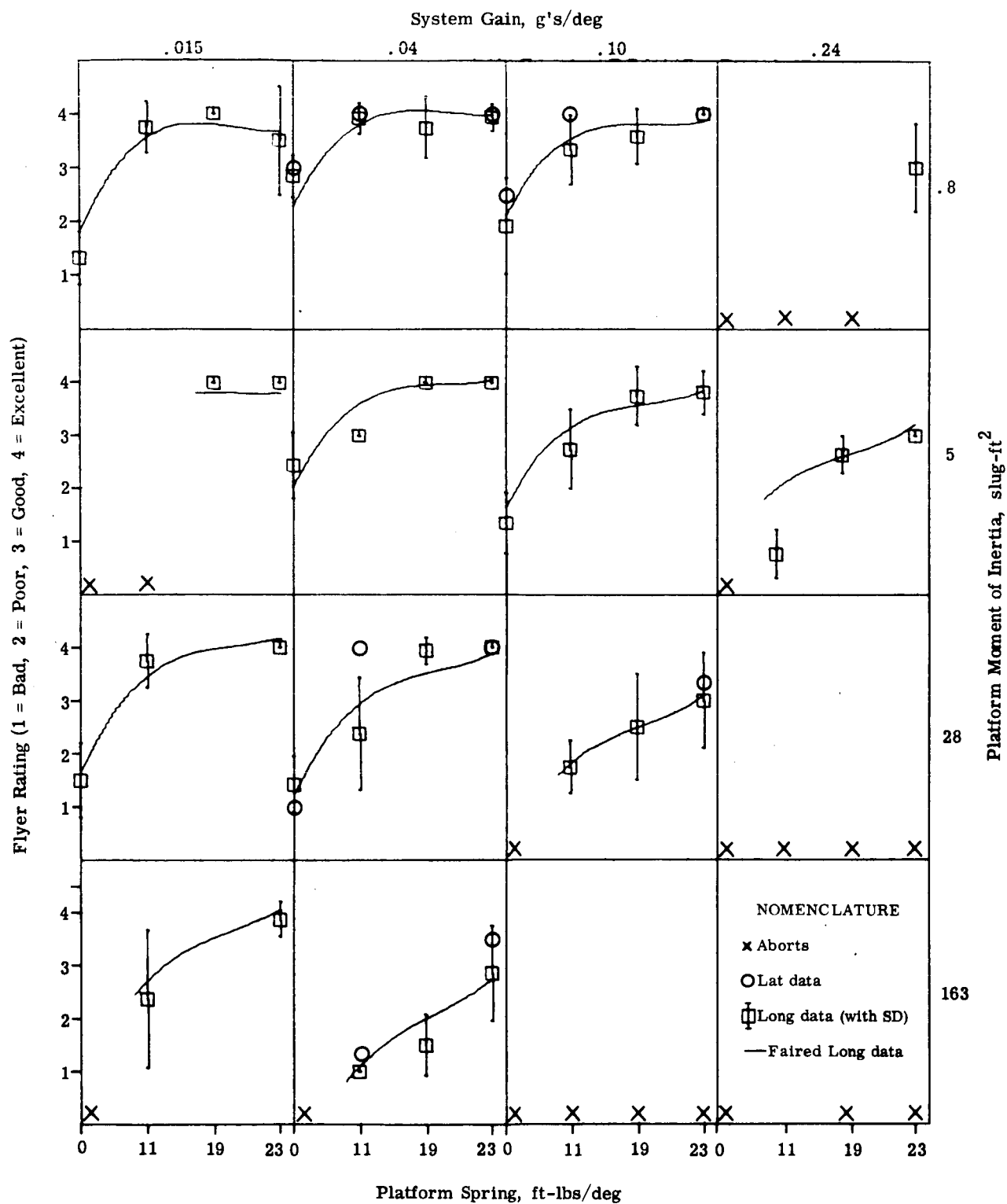


Fig. 10d Average Flyer Rating as a Function of Platform Spring (Gun Aiming Task)

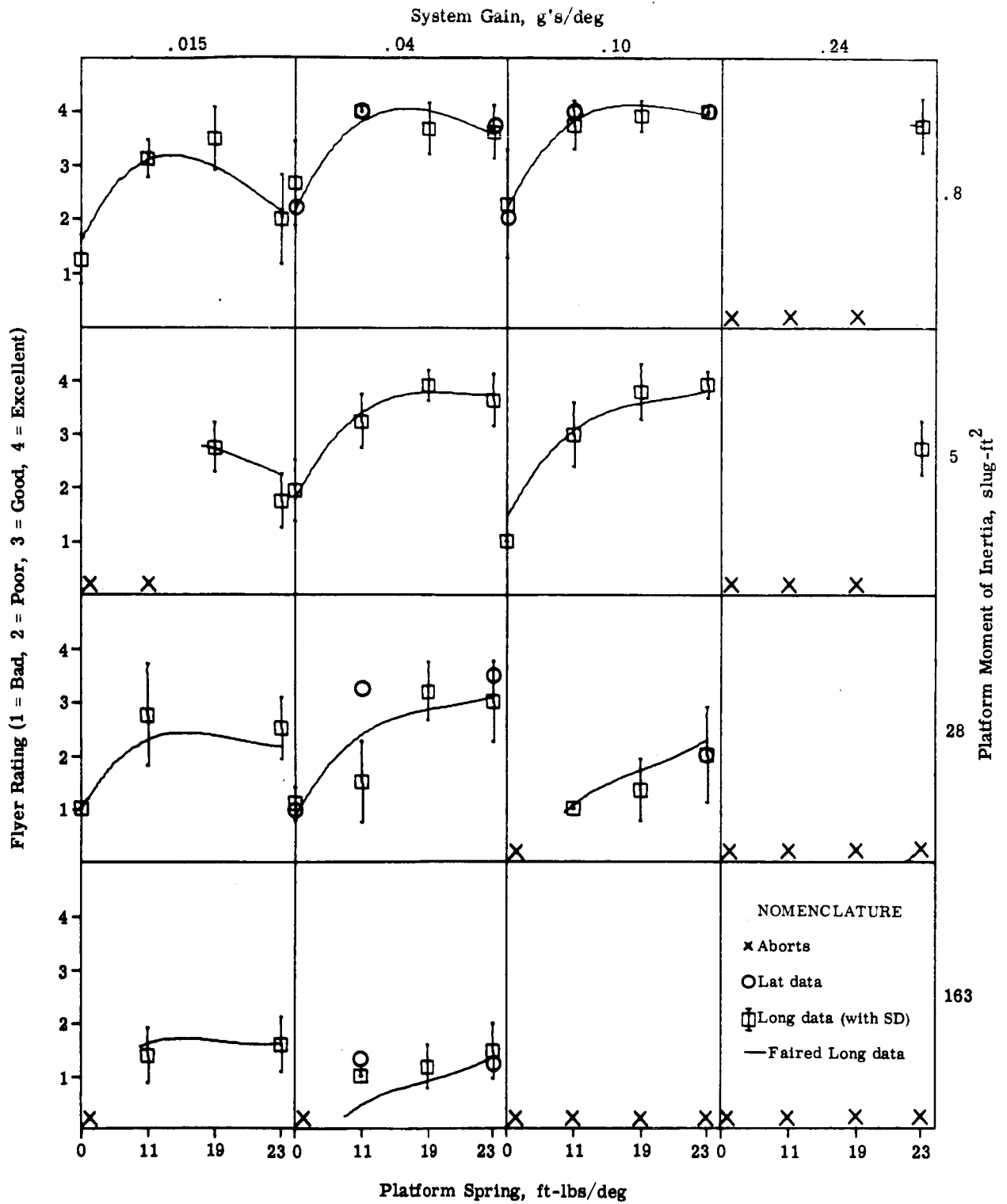


Fig. 10e Average Flyer Rating as a Function of Platform Spring (Tracking Task)

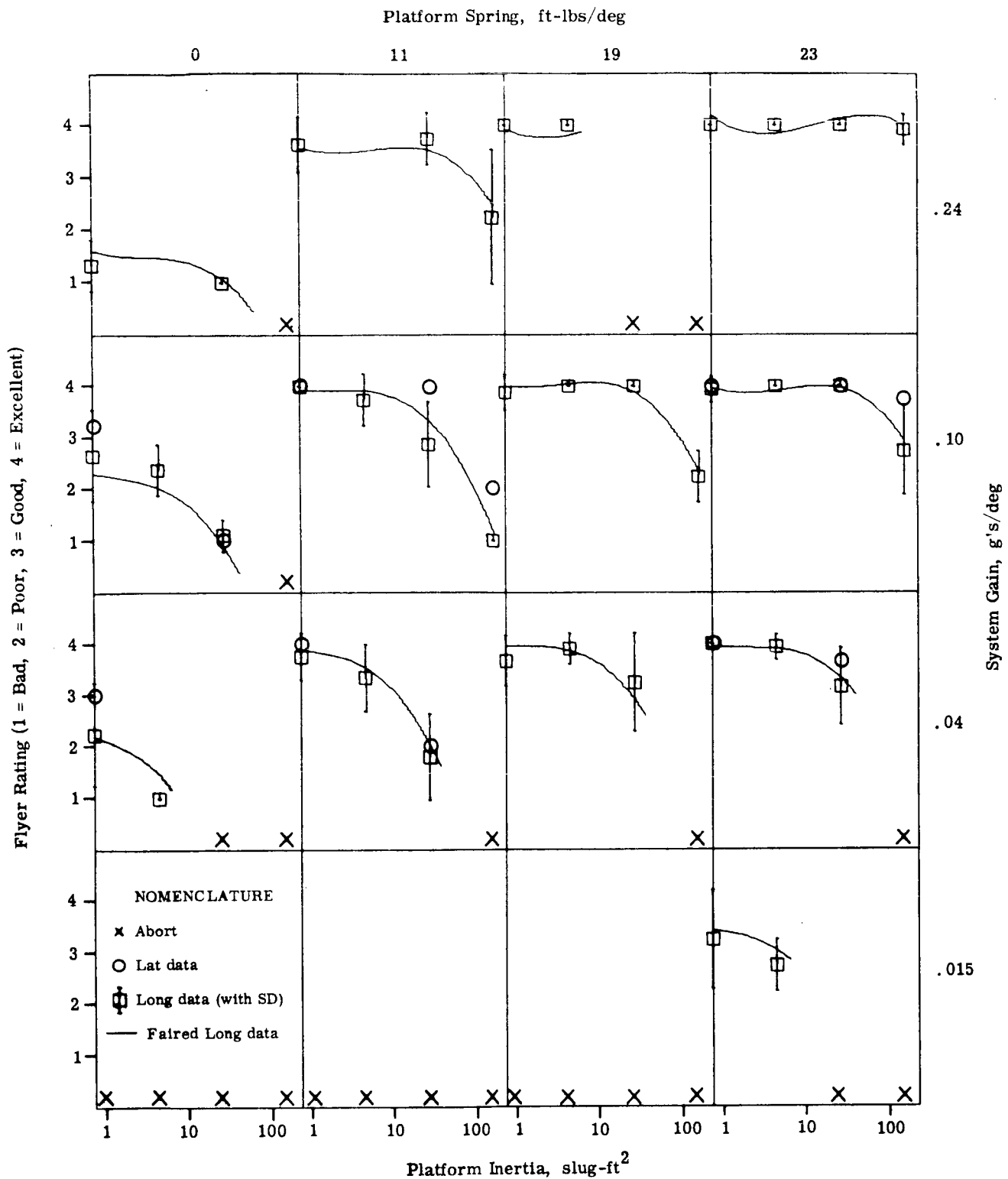


Fig. 11a Average Flyer Rating as a Function of Platform Moment of Inertia (Off-Board Dexterity Task)

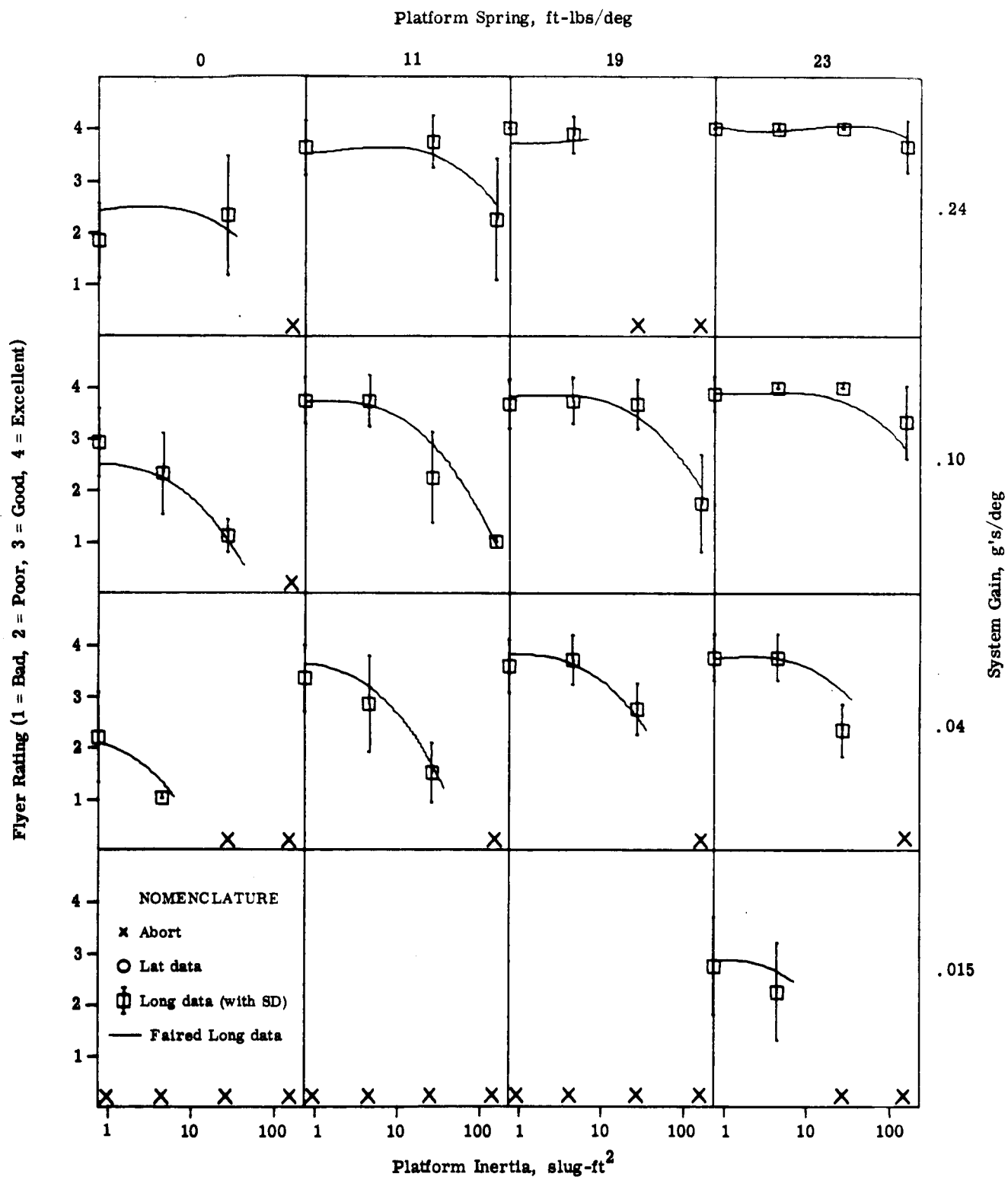


Fig. 11b Average Flyer Rating as a Function of Platform Moment of Inertia (Gross Dexterity Task)

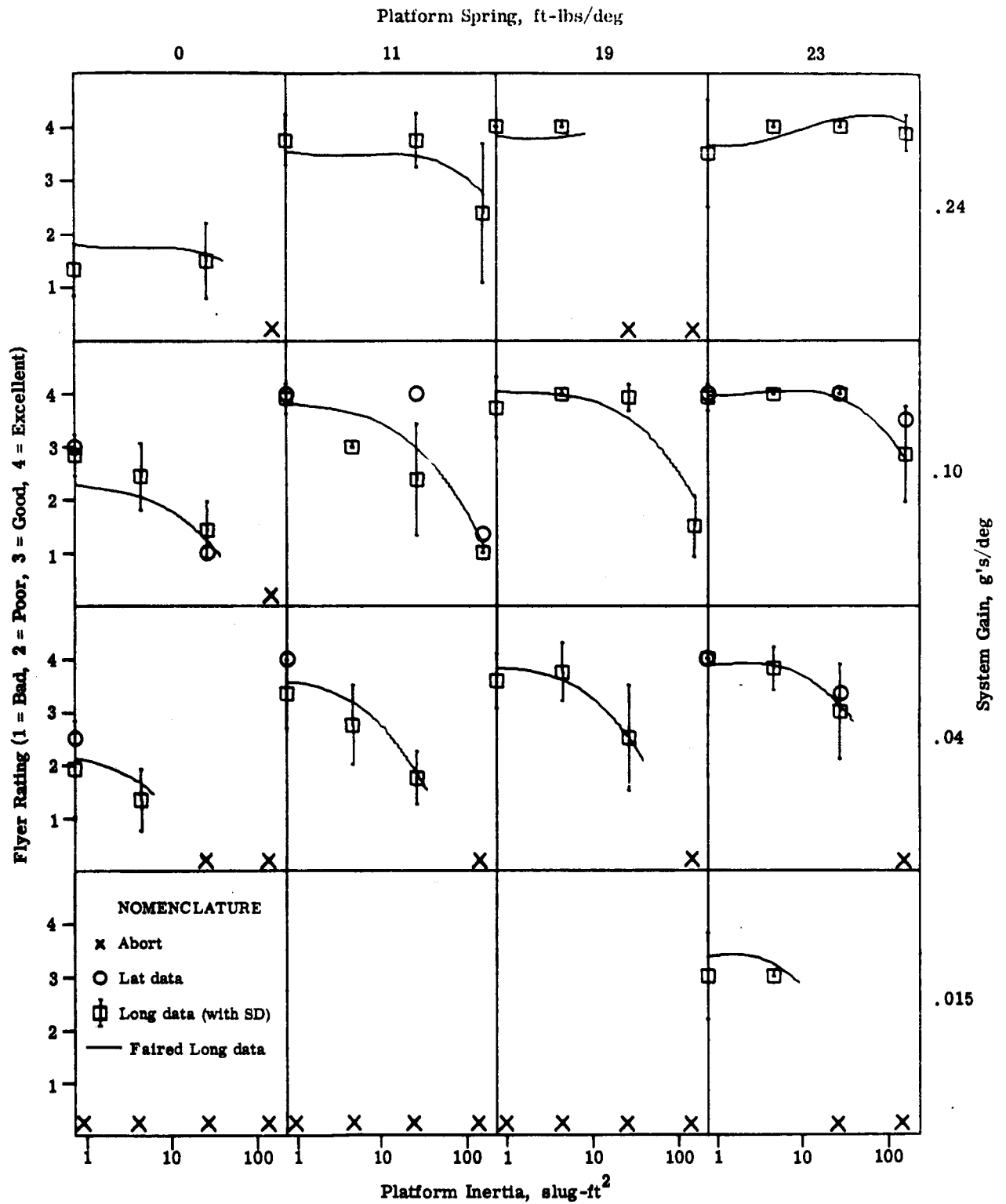


Fig. 11d Average Flyer Rating as a Function of Platform Moment of Inertia (Gun Aiming Task)

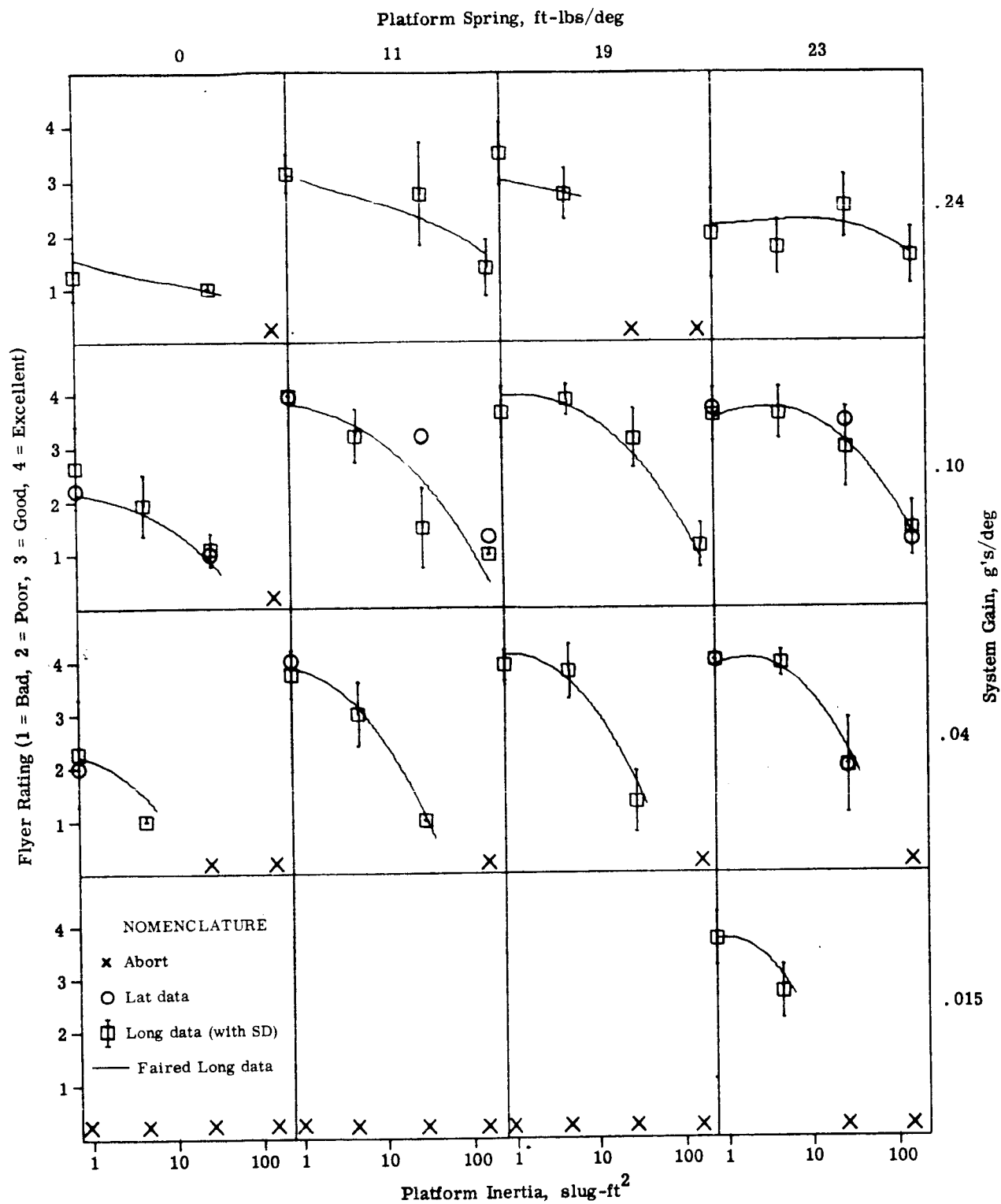


Fig. 11e Average Flyer Rating as a Function of Platform Moment of Inertia (Tracking Task)

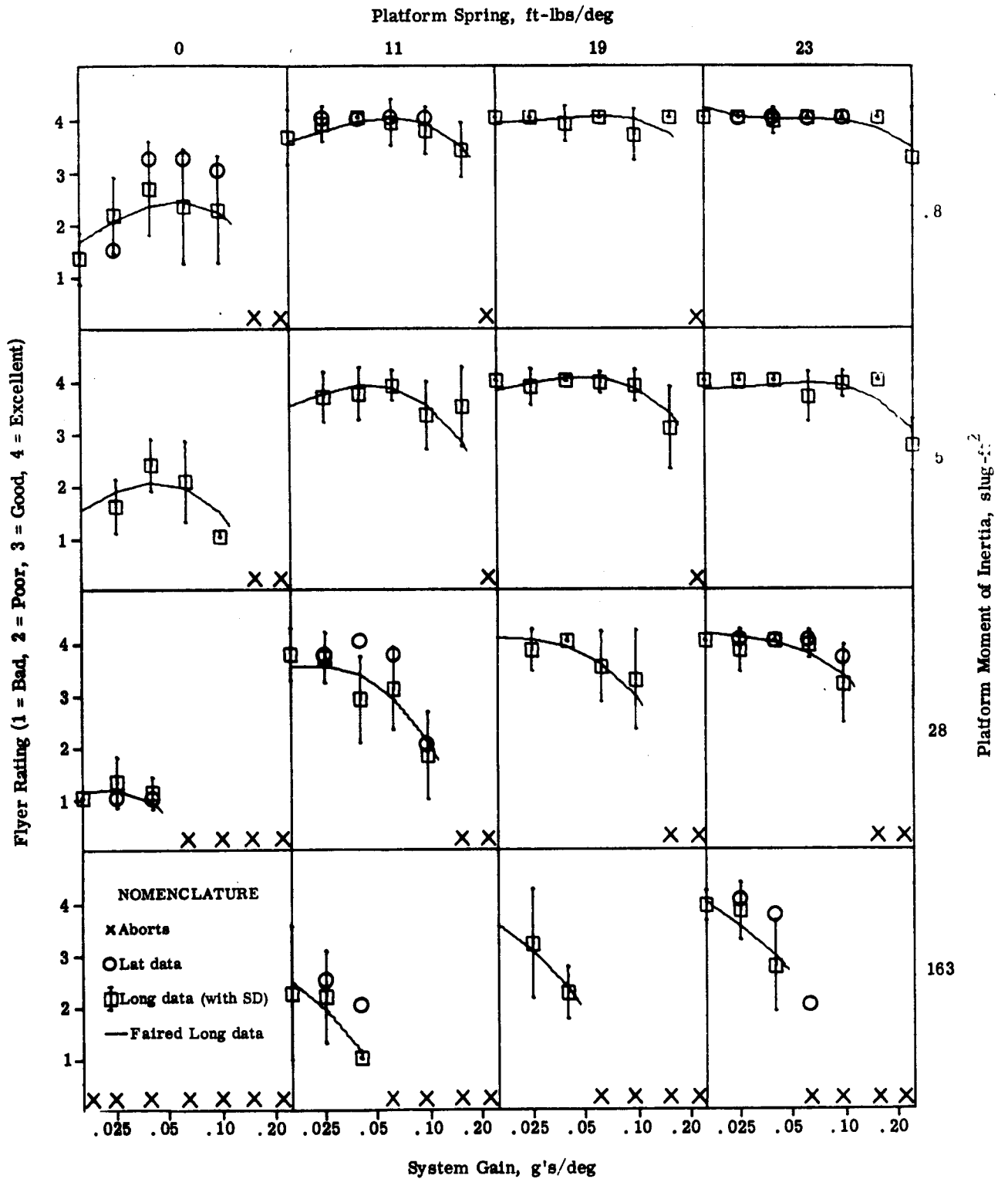


Fig. 12a Average Flyer Rating as a Function of System Gain (Off-Board Dexterity Task)

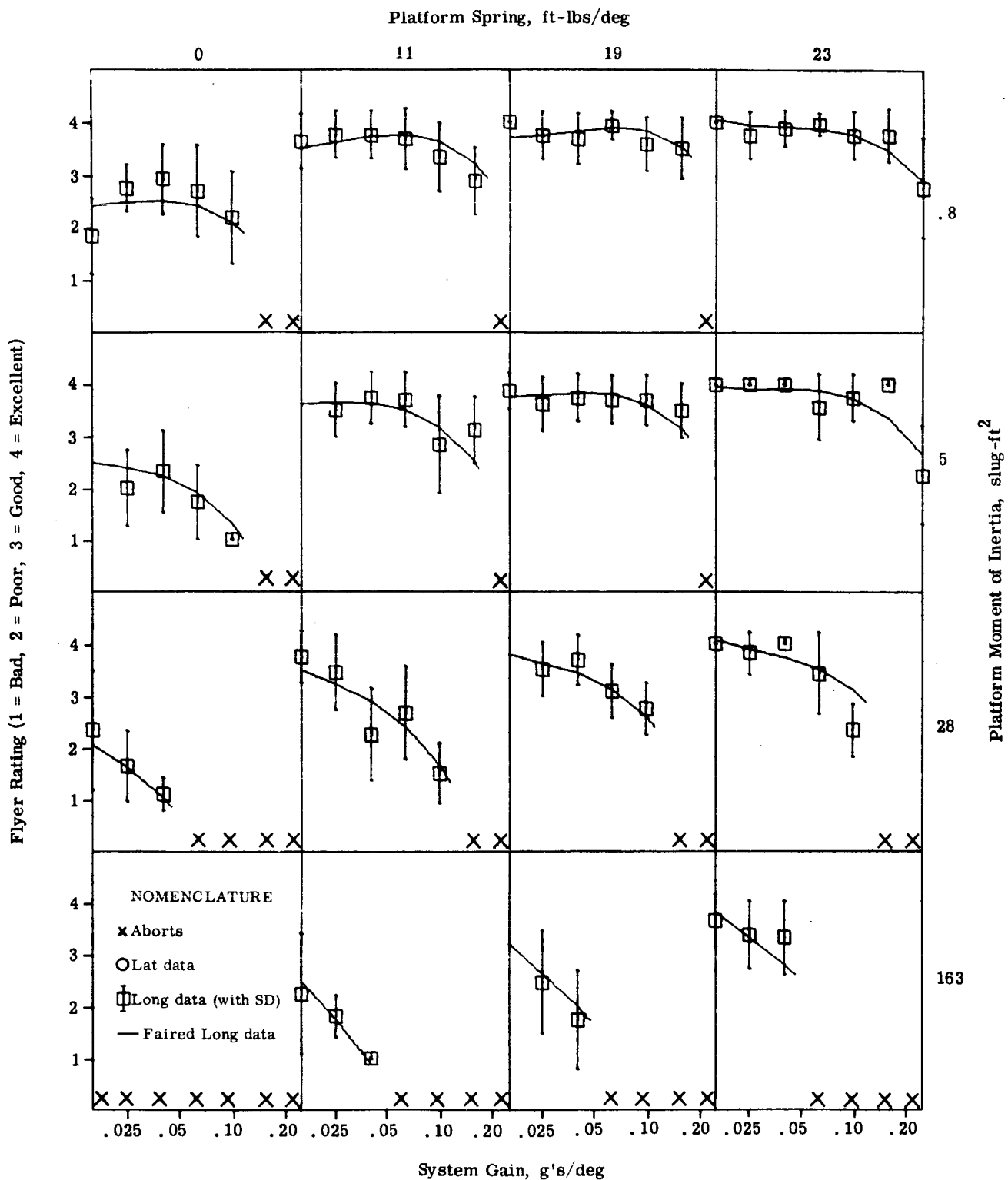


Fig. 12b Average Flyer Rating as a Function of System Gain (Gross Dexterity Task)

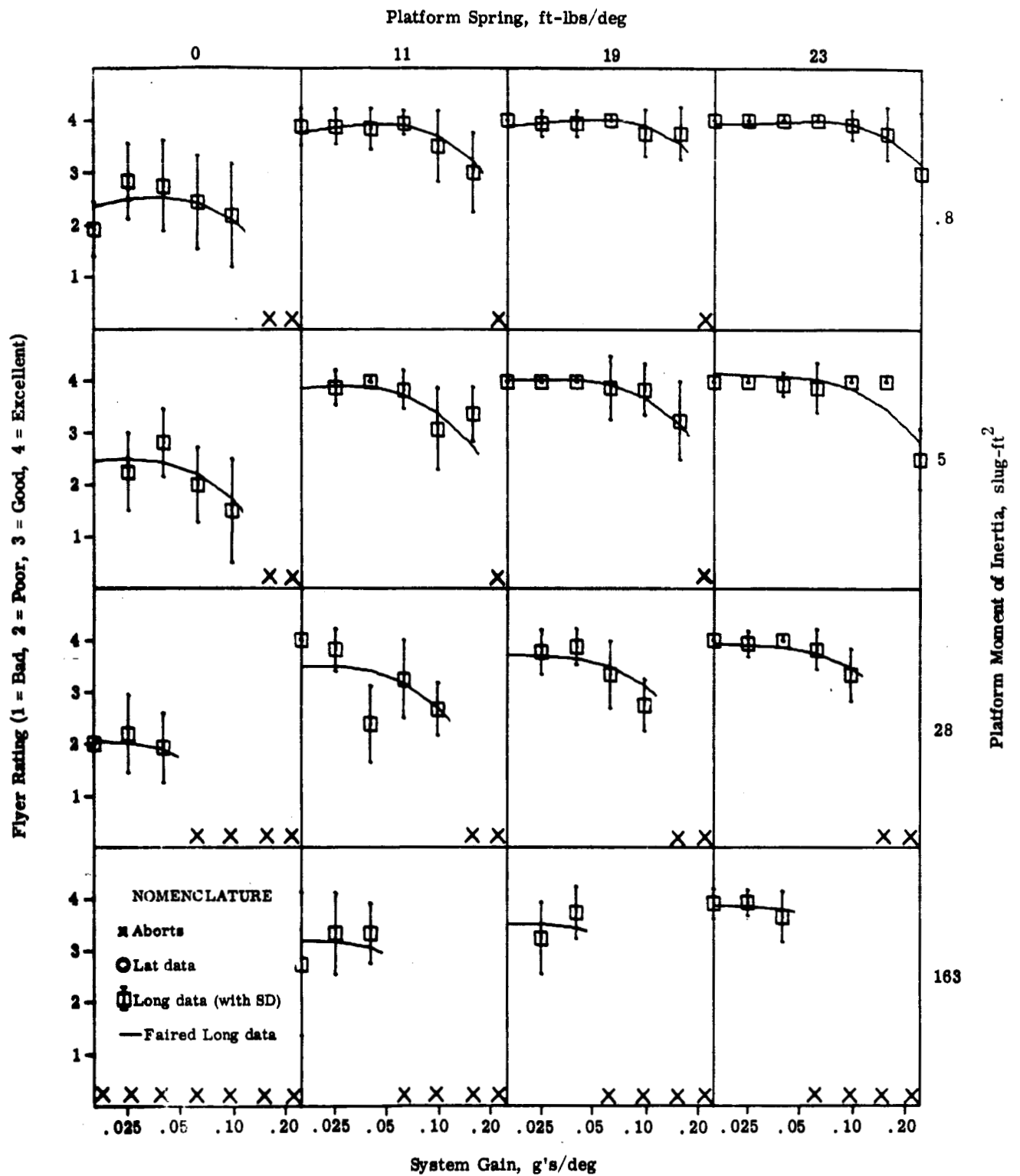


Fig. 12c Average Flyer Rating as a Function of System Gain (On-Board Dexterity Task)

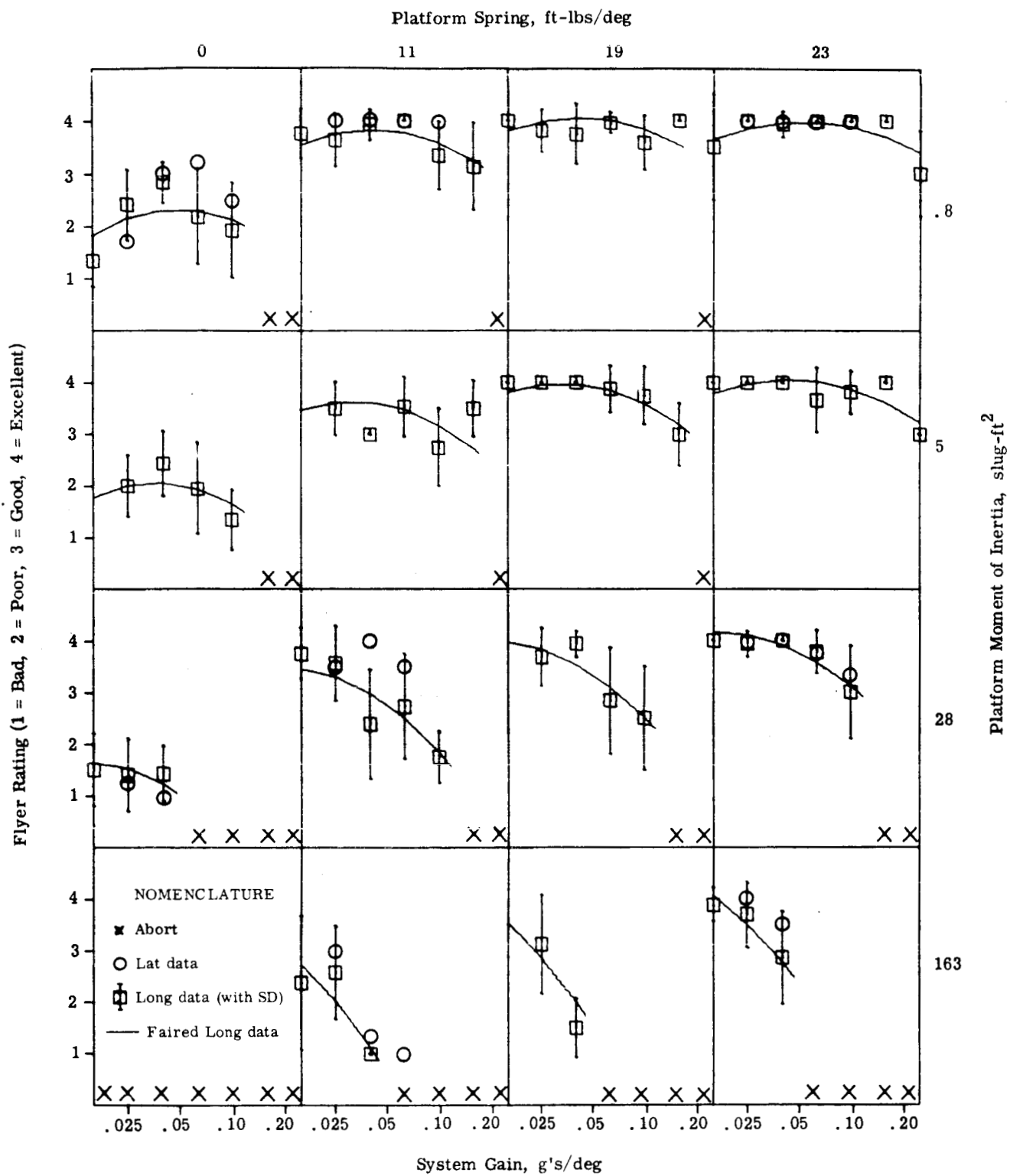


Fig. 12d Average Flyer Rating as a Function of System Gain (Gun Aiming Task)

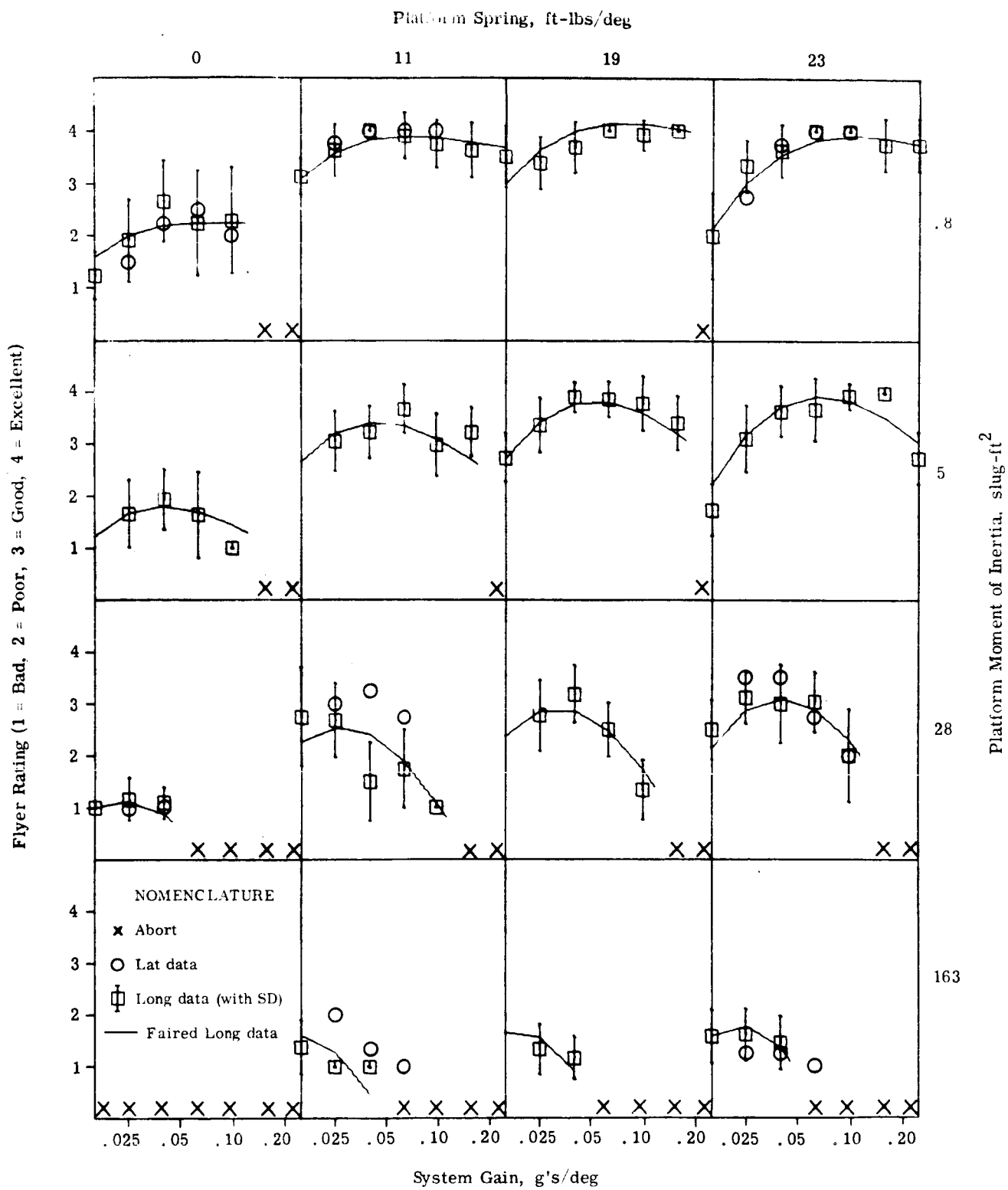


Fig. 12e Average Flyer Rating as a Function of System Gain (Tracking Task)

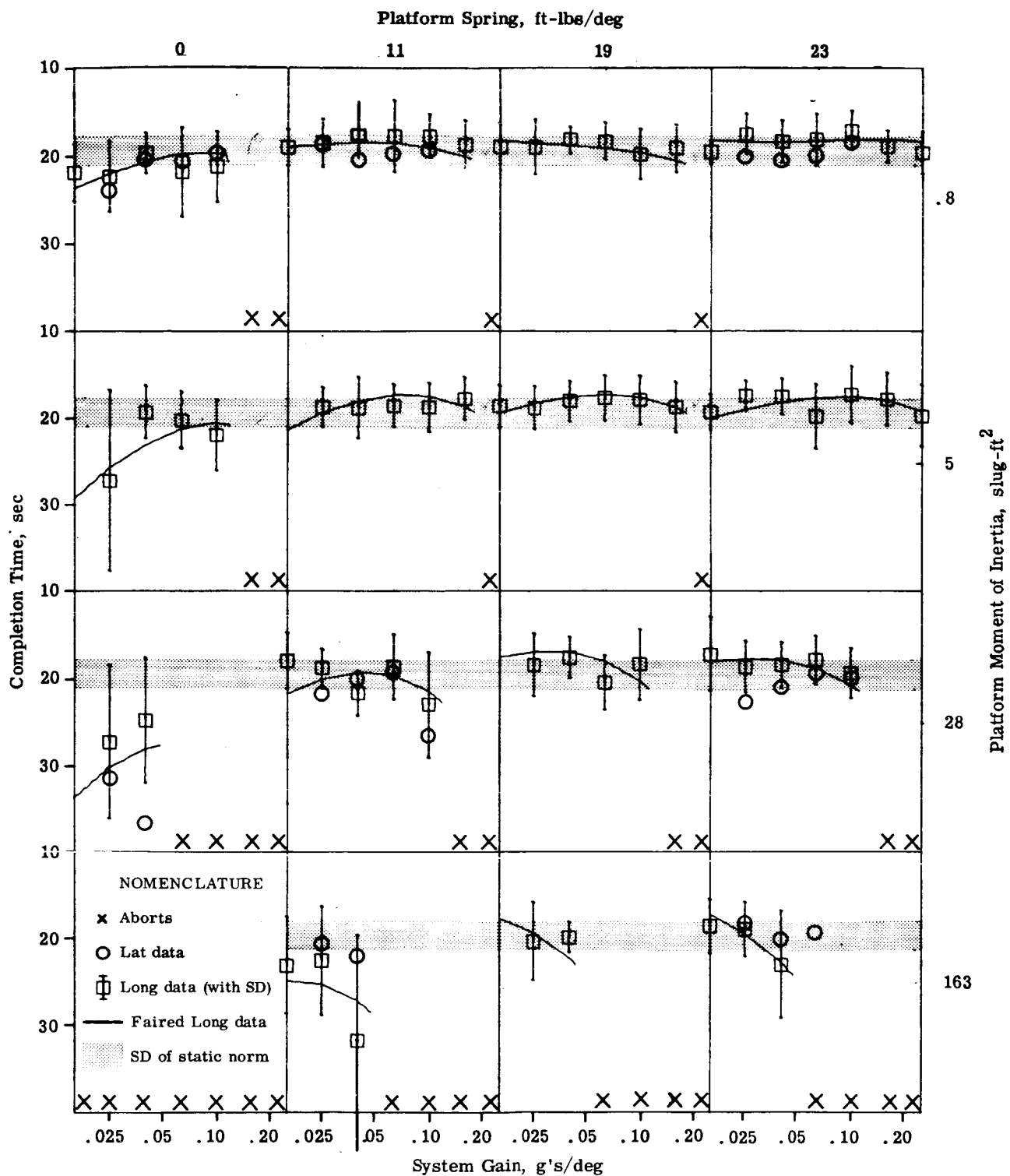


Fig. 13a Average Flyer Score as a Function of System Gain (Off-Board Dexterity Task)

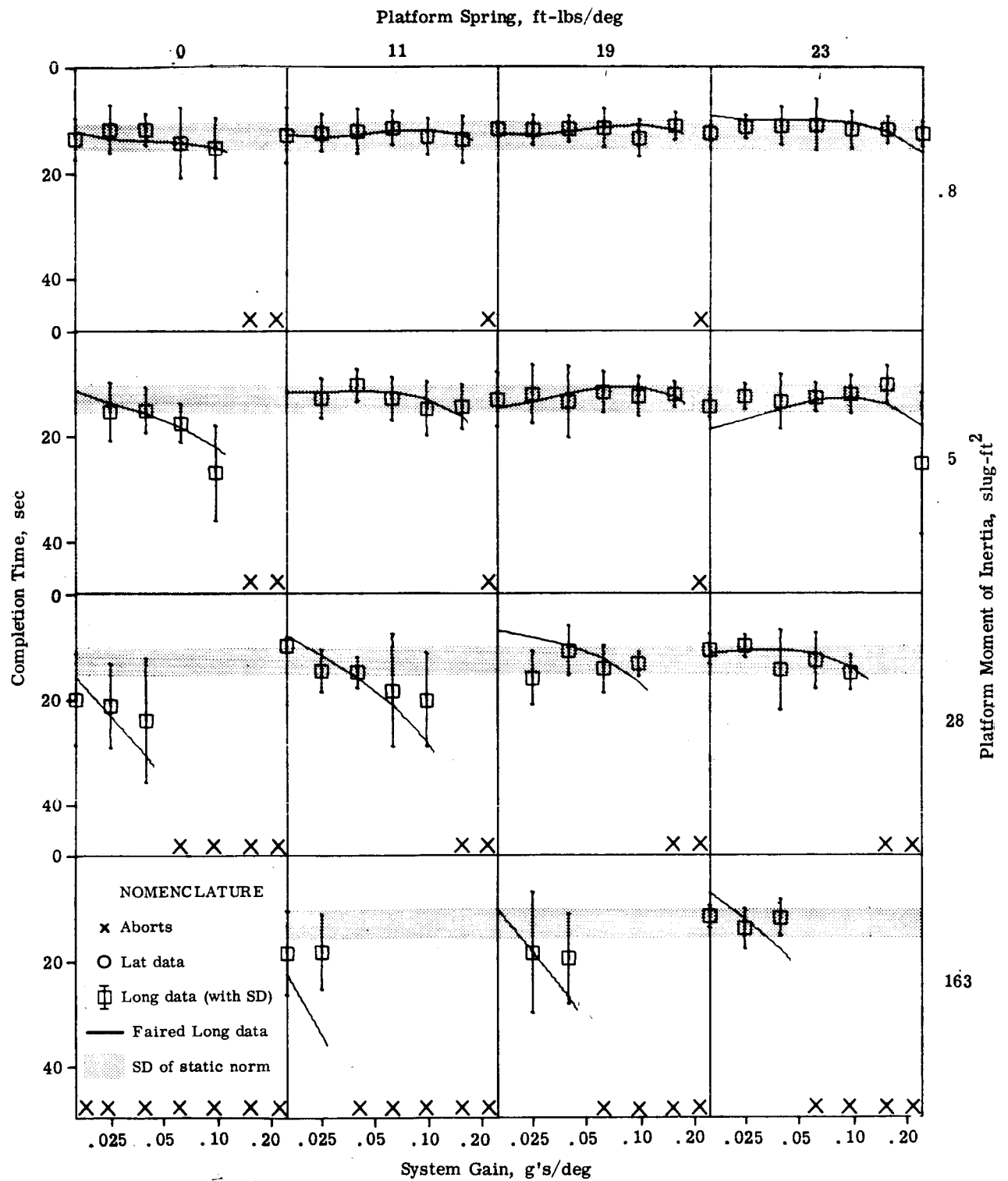


Fig. 13b Average Flyer Score as a Function of System Gain (Gross Dexterity Task)

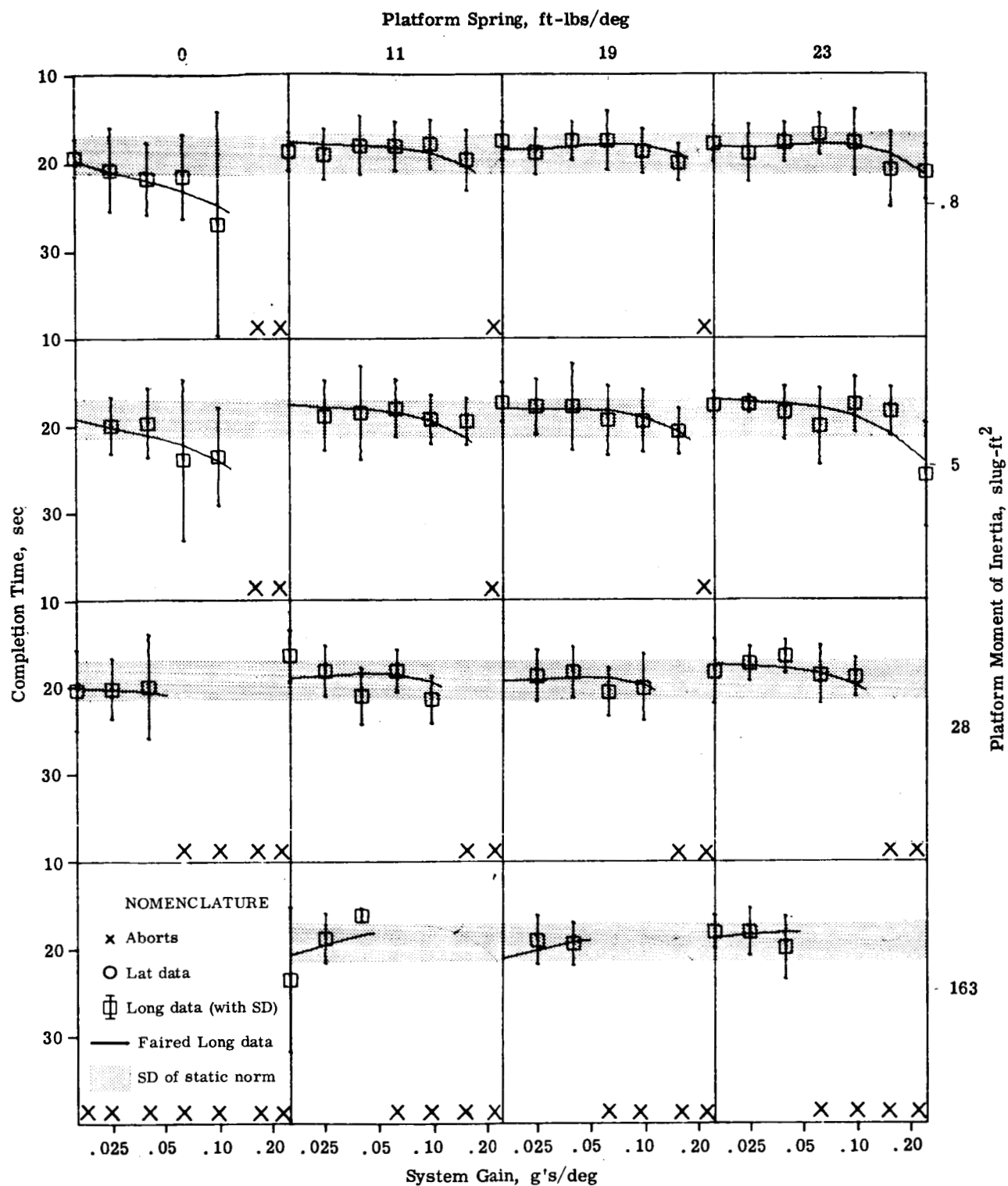


Fig. 13c Average Flyer Score as a Function of System Gain (On-Board Dexterity Task)

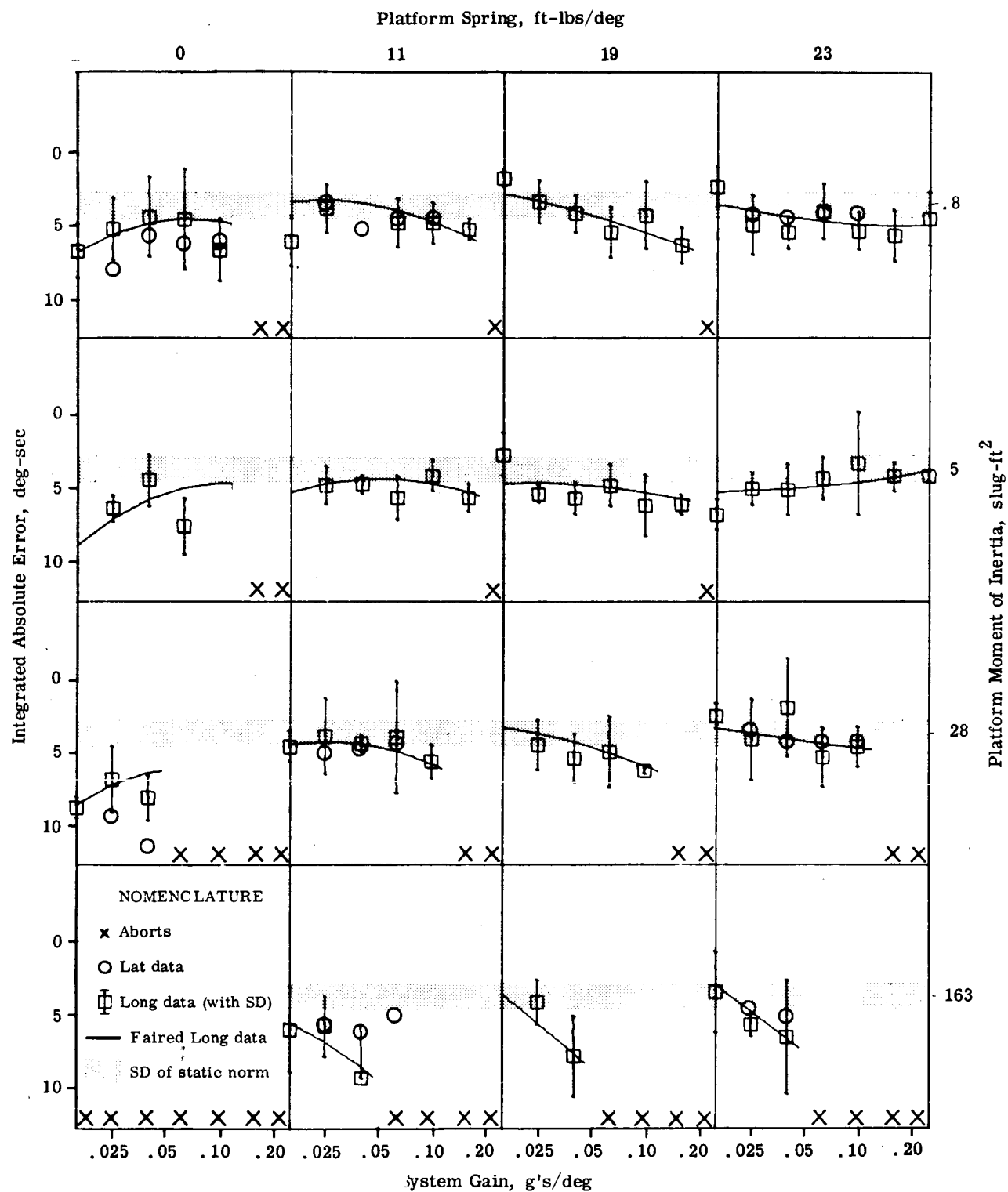


Fig. 13d Average Flyer Score as a Function of System Gain (Gun Aiming Task)

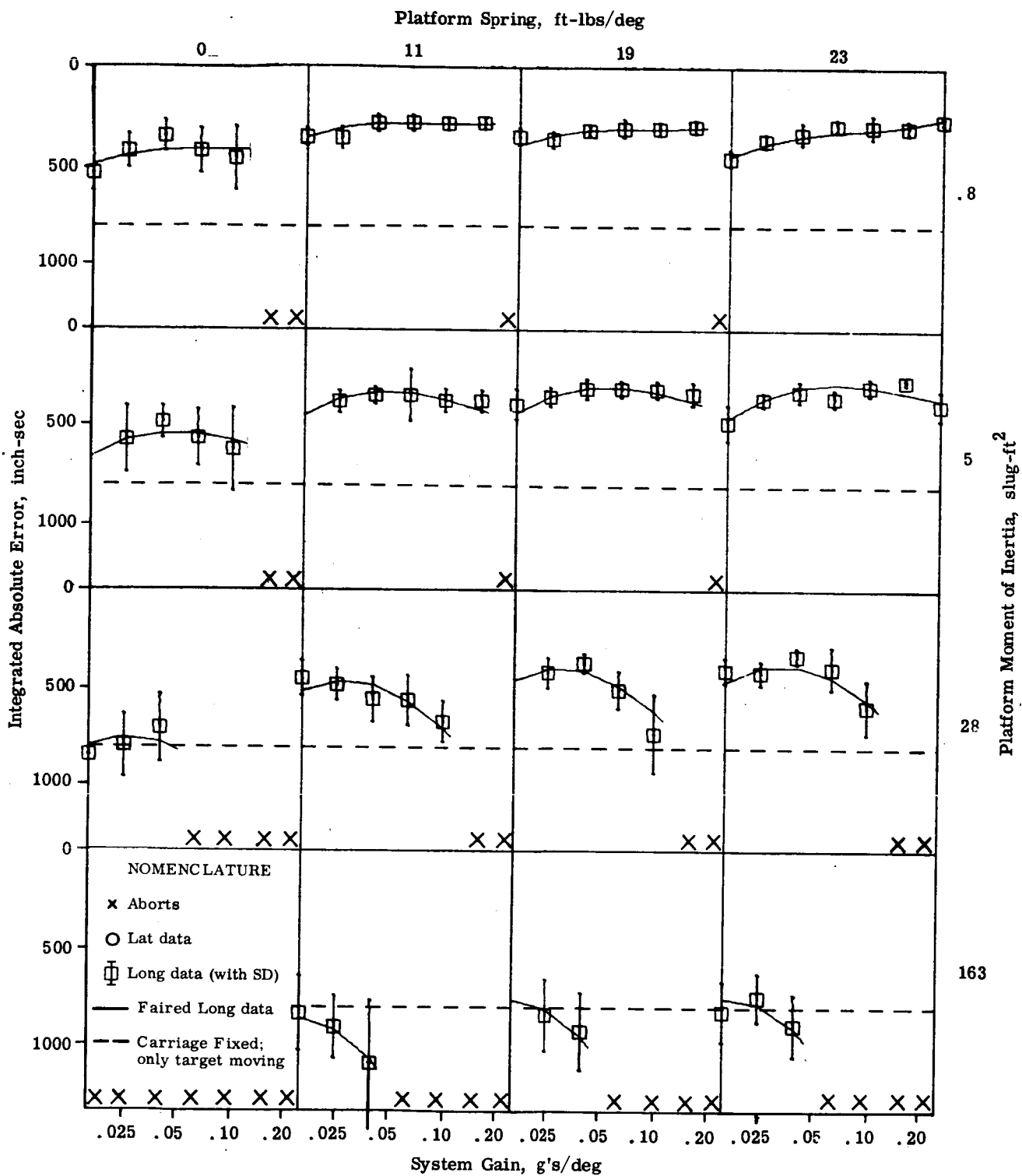


Fig. 13e Average Flyer Score as a Function of System Gain (Tracking Task)